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(71) Applicants: CALLING COMMUNICATIONS CORPORATION [US/US]; 1900 West Garvey Avenue South, Suite 200, West Covina, CA 91790 (US). ENDGATE TECHNOLOGY CORPORATION [US/US]; 500 Macara Avenue, Sunnyvale, CA 94086 (US). CONDUCTUS, INC. [US/US]; 969 West Maude Avenue, Sunnyvale, CA 94086 (US).

(71)(72) Applicant and Inventor: WITHERS, Richard, S. [US/US]; 575 East Remington Drive, #17D, Sunnyvale, CA 94087 (US).

(72) Inventors: LOCKIE, Douglas, Gene ; 12309 Saratoga Creek Drive, Saratoga, CA 95070 (US). BLASING, Raymond, R. ; 5510 Ora Street, San Jose, CA 95129 (US). JOHNSON, Edwin, F. ; 643 Cheyenne Drive, Sunnyvale, CA 94087 (US).

(74) Agent: GIACCHERINI, Thomas, Nello; Anglin & Giaccherini, 360 Forest Avenue, Suite 201, Palo Alto, CA 94301 (US).

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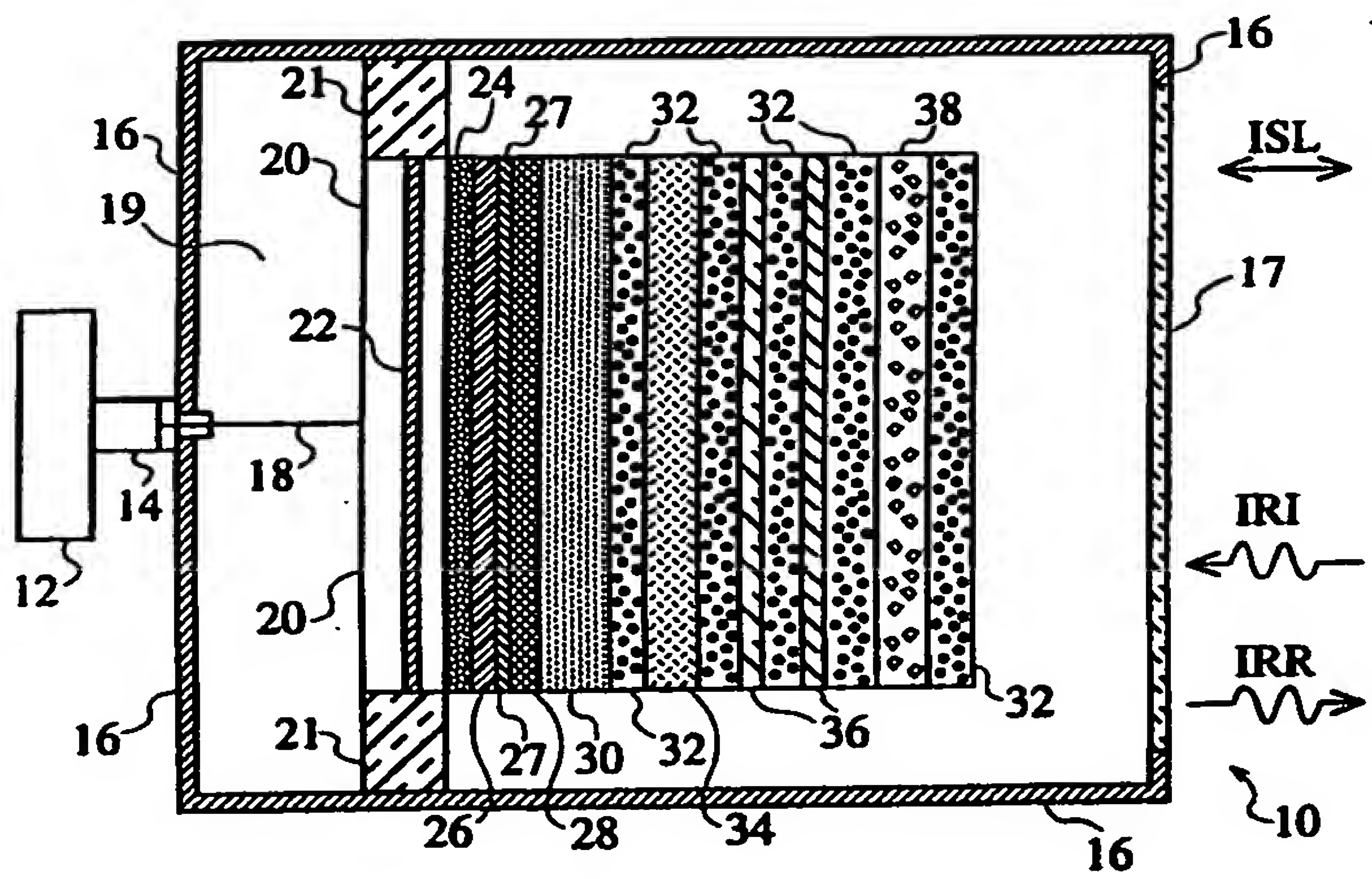

(57) Abstract

A superconducting millimeter wave array (10) is disclosed. In one of the preferred embodiments of the invention, the array (10) is enclosed in a cryogenic envelope (16) that has one side that is transparent to microwave radiation. A superconducting microstrip layer (24) formed on a saphire substrate (20) attached to the envelope (16) is coupled to transmit and receive circuitry via a signal waveguide (18). Each microstrip terminal (25) on the superconductor layer (24) is aligned with a slot (29) formed in a slotted ground plane (27) residing next to the superconductor layer (24). A heat reflective dielectric layer (26) is placed next to the superconducting layer (24), and is also adjacent to a layer of conductive radiating elements (30) and a layer of parasitic patches (35). Individual conductive radiating elements (31) and the parasitic patches (35) are also positioned in line with the microstrip terminals (25) and the slots (29) in the ground plane (22).

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Spacecraft Intersatellite Link for Satellite Communication System

DESCRIPTION OF THE INVENTION

TECHNICAL FIELD

The present invention relates to the field of satellite antennas. More particularly, this invention provides a wide-band, time-delay, electronically-steered, phased array satellite antenna system that includes a superconducting millimeter wave intersatellite link. The extremely low losses achieved by the invention will enable the construction and operation of a satellite communication system that offers continuous global coverage for voice, video and data transmissions among subscribers using personal, mobile and fixed terminals and gateways on land, on the seas and in the air.

BACKGROUND ART

Conventional public phone systems rely primarily on land lines and microwave repeaters to handle vast amounts of call traffic. Improvements of cellular networks have enhanced phone service by providing access to the land based system to customers using mobile phones in their vehicles or hand-held portable units. The increased capacity offered to the subscriber is relatively small compared to the number of subscribers using conventional fixed phones, since cellular service is limited to only those geographical regions that are densely populated. Cellular communication is often afflicted by poor performance when customers travel from one cell to another, or when they traverse the radio shadows projected by terrain or buildings.

One previous attempt to bypass the limits of conventional communications networks utilizes a transportable telephone that employs a satellite dish several feet in diameter to communicate directly with satellites in 22,300 mile geostationary orbits. The transponders on board these satellites then connect the caller directly to the land-based system, which directs their call through switches on the ground. These devices are heavy, difficult to transport, and are prohibitively expensive.

Other attempts to provide telephone services using a satellite constellation have been constrained by the difficulty of providing adequate bandwidths and complex beam steering capabilities. Building a network which includes intersatellite links that offers wide instantaneous bandwidth and precise electronic beam steering antenna arrays is difficult using conventional technology. Line losses and dispersion effects at millimeter wave frequencies impose severe obstacles when conventional hardware is employed. Furthermore, conventional systems are heavy, need excessive DC power and are very expensive.

Public phone companies do not currently offer continuous world-wide voice, video and data service to subscribers using personal or mobile terminals without the use of costly and large antenna systems. Commercial spacecraft and transponders that are presently on orbit do not generally possess the power capacity to communicate directly with terminals that are not coupled to an antenna dish that are at least a few feet in diameter. The service which is available is extremely limited and too expensive for use by all but a few. The problem of providing an economically viable network for voice, data, and

video which can be used at any time by subscribers all over the world has presented a major challenge to the communications business. The development of a light weight, high power satellite system including very low loss intersatellite links which would enable the entire network to transmit and receive radio signals among portable, mobile, and fixed terminals on the land and sea and in the air without the intermediate steps of routing traffic through land-based equipment would constitute a major technological advance and would satisfy a long felt need within the electronics and telephone industries.

DISCLOSURE OF THE INVENTION

The *Spacecraft Intersatellite Link for Satellite Communication System* comprises an advanced active element, phased array antenna combined with a superconducting millimeter wave array. The present invention utilizes wide-band, electronically steerable, time delay techniques to provide extremely high gain signals to users of personal, mobile and fixed terminals and users connected to terrestrial gateways. By incorporating these novel antenna systems on a constellation of low Earth orbit spacecraft, phone customers across the globe will be able to communicate voice, video and data without relying exclusively on traditional land-based networks that are vulnerable to traffic congestion and unexpected failures. The present invention will offer a revolutionary expansion of the communications capacities that are currently available.

The present invention may be implemented using a variety of spacecraft and antenna designs. In the preferred embodiment, a spacecraft called "*Callingsat*"™ octagonal panel and eight radiating arms is employed. In a first alternative embodiment called "*Domesat*"™, a generally hemispherical configuration of hexagonal antenna facets fabricated from ultra-light weight honeycomb materials and advanced composites is utilized. In a second alternative embodiment, a spacecraft resembling a torus called "*Gearsat*"™ us used to implement the invention. Gallium-arsenide (GaAs) millimeter wave integrated circuits (MMIC) coupled to each antenna panel handle call traffic. High temperature superconductor components are used to implement a millimeter wave intersatellite link that is extremely power efficient, small and light weight. The present invention is designed to cost a fraction of the cost of a comparable system using conventional technology. The invention employs a time delay steered, planar array antenna using a semi-active transmit and receive architecture. The semi-active architecture uses only one transmitter and one receiver, as compared to a fully active design, which, in this case, would need 1,024 transmit and receive modules.

In one of the preferred embodiments of the invention, the superconducting millimeter wave array is enclosed in a cryogenic envelope that has one side that is transparent to microwave radiation. A superconducting microstrip layer formed on a sapphire substrate attached to the envelope is coupled to transmit and receive circuitry via a signal waveguide. Each microstrip terminal on the superconductor layer is aligned with a slot formed in a slotted ground plane residing next to the superconductor layer. A heat reflective dielectric layer is placed next to the superconducting layer, and is also adjacent to a

layer of conductive radiating elements and a layer of parasitic patches. Individual conductive radiating elements and the parasitic patches are also positioned in line with the microstrip terminals and the slots in the ground plane. The array also includes spacers, polarizing layers and a dielectric mirror.

The array is part of a 60 GHz intersatellite link that offers a 600 mile range. The link provides a 40 dB gain, with 500 MHz, 1 GHz and 2 GHz bandwidth capabilities. These bandwidths correspond to approximately 1 watt to 4 watt RF power levels coupled to the 40 db gain antenna. The link can be steered plus or minus 25 degrees. Sidelobes are very critical, so the design uses an aperture of slots coupled to radiating patches, which essentially eliminates radiation contributions from the beamforming feed network.

An appreciation of other aims and objectives of the present invention and a more complete and comprehensive understanding of this invention may be achieved by studying the following description of a preferred embodiment and by referring to the accompanying drawings.

A BRIEF DESCRIPTION OF THE DRAWINGS

Figure 1 is perspective view of a satellite that includes a hemispherical array of hexagonal antenna facets and fully extended rectangular solar panels. The satellite configuration illustrated in Figure 1 is utilized in an alternative embodiment of the invention.

Figure 2 depicts a schematic diagram of the satellite similar to the one illustrated in Figure 1. Figure 2 also reveals three sets of electronically steered beams produced by the hexagonal antennas and the circular and elliptical footprints which the beams illuminate on the Earth's surface.

Figure 3 illustrates a pattern of multiple beams generated by the satellite shown in Figures 1 and 2.

Figures 4 & 5 present plots of satellites in one orbital plane showing a number of inter-satellite links (ISLs).

Figure 6 reveals a schematic diagram of a gallium arsenide millimeter wave integrated circuit (GaAs MMIC) time delay network.

Figure 7 shows a schematic of the active lens, which includes a large number of the time delay networks shown in Figure 6.

Figure 8 is a schematic illustration of an active lens which incorporates a time delay steered antenna array.

Figure 9 is a schematic diagram of intersatellite links.

Figure 10 shows the basic design of a gateway terminal.

Figures 11, 12 and 13 supply views of alternative satellite designs that may be utilized in concert with the present invention.

Figure 14 is a schematic depiction of a superconducting millimeter wave array. The reader should note that the various elements and layers are not shown in proper proportion or dimension, but

are portrayed only to convey the geometric relationship of the various elements of one of the preferred embodiments of the invention.

Figure 15 exhibits a 60 GigaHertz (GHz) rectangular array. The array comprises a deposited and etched layer of superconducting microstrip lines.

Figure 16 is an enlarged portion of Figure 15, revealing the details of the alignment of a microstrip terminal, a slot, and a conductive radiating element.

Figure 17 illustrates a 32 by 32 array of conductive radiating elements.

Figure 18 reveals the alignment of the superconducting microstrip layer depicted in Figure 15, a slotted ground plane layer, and the layer of conductive radiating elements shown in Figure 16.

Figure 19 portrays a signal waveguide, a cryogenic heat pipe, and a conduit for power and control wiring passing through the cryogenic envelope pictured in Figure 14.

Figures 20 and 21 show the construction of the sapphire substrate depicted in Figure 14. The substrate illustrated in Figures 20 and 21 includes a cryogenic heat pipe subassembly.

Figure 22 exhibits the coupling of optical fibers through a transmissive dielectric material.

Figure 23 presents a schematic view of optical fibers that deliver photons to localized areas on the superconducting layer to control the operation of the array.

Figure 24 is a simplified view of superconducting switch.

Figures 25 and 26 supply diagrams that explain time-delay beam steering methods employed by one of the preferred embodiments of the present invention.

Figure 27 is perspective view of the satellite used in the preferred embodiment. This "*Callingsat*"™ design comprises a central octagonal panel and eight radiating arms.

Figure 28 depicts the underside of "*Callingsat*"™ as viewed from Earth.

Figure 29 is an enlarged depiction of the underside of "*Callingsat*"™ which illustrates transmit and receive antennas.

BEST MODE FOR CARRYING OUT THE INVENTION

Figure 1 depicts a satellite design called *Domesat*™ that may be used to implement one of the preferred embodiments of the present invention. This perspective view shows a satellite S which is a member of a constellation of satellites in low Earth orbit that provides communications services to portable, mobile and fixed terminals and gateways P, M, F & G. The system supplies continuous global voice, data, and video services to subscribers on land, sea and air. In the preferred embodiment, the constellation comprises 40 sets of satellites operating in 21 orbital planes. In an alternative embodiment, the constellation includes 29 sets of spacecraft flying in 29 orbits. The entire fleet travels around the Earth at a height of 700 km (435 miles).

As shown best in Figure 1, each satellite S includes an array of antennas A. Most of the separate antennas are hexagonal facets H that are mated along their six-sided perimeters to other facets

H. As a result, the satellite body takes the shape of a slightly flattened, hemispherical shell. The antennas that service subscribers are generally pointed toward the Earth E and away from the zenith Z. Some of the antennas A may serve as intersatellite link antennas. In Figure 1, the two rectilinear solar panels SP which trail the body of the spacecraft S are shown in their unfurled positions.

Figure 2 represents the patterns or "footprints" Ta, Tb, and Tc, of the beams B formed on various portions of the Earth's surface E. The set of beams marked Ba travel the shortest possible distance from the spacecraft S to the Earth E because these beams Ba travel along a pathway which runs from the ground to the zenith Z and back. The area on the surface illuminated by this set of beams Ba results in a generally circular footprint Ta. Other sets of beams, like those marked Bb and Bc, are more inclined to the line that runs from the center of the Earth toward the zenith Z, and the areas Tb and Tc irradiated by these beams Bb and Bc become progressively more elliptical as the angle of inclination becomes larger.

Figure 3 presents a schematic depiction of the pattern of multiple beams generated by the satellite S shown in Figures 1 and 2. The beams B comprise a complete set of line-of-sight waves generated by one spacecraft S. The distance on the Earth's surface between each line radiating from the satellite represents a coverage area of 20km per beam.

Figures 4 and 5 are geometric plots which include sight lines between neighboring satellites S that travel along the same orbit. Several spacecraft in a single orbital plane can communicate with each other if they are located above the horizon of the Earth E. Satellites communicate among one another over intersatellite links (ISLs) using a 60 Ghz frequency band. In one of the preferred embodiments, a 1.5 foot antenna provides approximately 45 Db of gain which supports a practical inter-satellite link. Four fixed and two electronically steerable antennas are used on each *Domesat*™ for ISL links. Optional links in the orbital plane may increase the number of ISL antennas to ten, eight of which would be fixed and two of which would be steerable.

The antennas A carried by the spacecraft are designed to transmit and receive signals from terrestrial units that are located within the footprints T produced by the electronically steered beams B. In the preferred embodiment of the invention, only those terrestrial units that are within the conical line-of-sight region that is defined by a minimum elevation angle, or "mask angle," of 40 degrees can be serviced by a particular spacecraft. In an alternate embodiment of the invention, a minimum mask angle of 15 degrees is employed. The hexagonal facets H and their related signal processing circuitry produce hexagonal coverage patterns. In one embodiment of the invention, the radius to the center of each of the six sides of each facet H is 6.2 degrees, while the radius to the six corners of the hexagon subtends 7.16 degrees. A spacing of 12.41 degrees allows for 29 hexagonal coverage patterns in each orbital plane. A similar spacing along the equator results in 29 orbital planes. This configuration of hexagonal facets offers double coverage in the equatorial regions and up to eight-fold coverage at higher latitudes, where larger numbers of subscribers are located. By selecting an odd number of satellites and planes,

the center of the descending patterns will fall on the seams of the ascending patterns. This selection insures that virtually every region on the surface of the Earth E between the latitudes of 70 degrees North and South will be serviced by the constellation.

The spaceborne antennas A are capable of providing a gain of 45 dB at the periphery of each footprint T and 42 dB at the nadir position. Because the beams generated by the spaceborne antennas A are so powerful, Earth-based terminals can incorporate low power antenna designs which substantially eliminate any radiation hazards that might otherwise harm the user. Each antenna uses a combination of the 20 and 30 Ghz frequency bands for satellite to ground communications. In the preferred embodiment, each antenna propagates 64 simultaneous beams which are multiplexed to 1,024 positions. Beams B aimed at the horizon possess an elliptical, as opposed to a circular or polygonal, shape to compensate for the low grazing angle, so that a constant Earth coverage footprint T is maintained. Uncorrected beams have an elliptical ground pattern which degrades spectral reuse efficiency. Electronic beam steering also permits the independent control of directivity gain and power gain. The beam steering provides a convenient method of correcting power levels during rain fades. The transmitted power gain from the satellite can be increased on transmit to overcome downlink fading. Satellite receive power gain can be increased during reception to overcome uplink fading. The use of these two techniques overcomes possibly poor communication performance during rainy weather conditions. In an alternative embodiment, the antenna A propagates 256 simultaneous beams B which are each multiplexed to 4,096 positions.

Signal processing components residing in the spacecraft include GaAs MMIC filters and are responsible for electronically steering active antenna arrays on board each satellite. Figure 6 reveals a schematic diagram of a GaAs MMIC time delay network TDN. In the preferred embodiment of the present invention, a circuit Model No. TD101 produced by Pacific Monolithics, Inc. of Sunnyvale, California is employed as the time delay network. Other more conventional time delay networks may also be employed. The electronic steering is accomplished by using these time delay networks TDN to create an active lens AL. The focal point of the lens is related to the directivity gain of the antenna A and can be controlled electronically. The ability to control the directivity gain is important for communications satellites in low Earth orbit because less gain is needed when a cell is addressed at the satellite nadir than when a cell is addressed at the periphery of the satellite footprint T. It is also desirable to increase the directivity gain in the elevation plane when addressing a cell at the satellite footprint periphery. The active lens AL incorporated in the present invention allows these variable directivity gains to be implemented without the reduction in efficiency that is associated with conventional antenna arrays.

Figure 7 shows a schematic of the active lens AL, which includes a large number of the time delay networks TDN shown in Figure 6 connected to radiating elements RE. The active lens AL illustrated in Figure 7 is the microwave analog of an optical lens. By increasing the time delay for the

signal paths in the center of the active lens AL with respect to the edge of the active lens AL, the focal length of the lens can be changed electronically, which, in turn, changes the directivity gain of the antenna A.

The present invention provides electronic steering which is sufficiently accurate to implement a practical gain variation in the 42 dB to 45 dB regime. For example, changing the radius of a radiation pattern by 200 meters at a range of 1200 kilometers requires a time delay control of 4 picoseconds for a 45 dB gain antenna array with dimensions of 1.2 meters on a side. Active lens control for the 42 to 45 dB range (in a 20/30 GHz system) requires time delays on the order of 4 picoseconds to 35 picoseconds.

The active lens AL can be constructed using one of two techniques. The first, which is depicted in Figure 7, utilizes a conventional lens that includes many pairs of receive and transmit antennas that are each connected in series with an active time delay network TDN. The second technique, which comprises the preferred embodiment of the invention, is exhibited in Figure 8. The time delay steered array TDSA comprises a feed FD, switches SW, coupled through transmission lines TL and time delay paths TDP to amplifiers AMP which precede the time delay active lens TDAL and radiating elements RE behind the array face AF. The switched time delay networks TDN in the corporate feed accomplish beam steering functions. The time delay networks TDN can be adjusted for either fine gain beam steering (a few degrees) or for changing the directivity gain of the antenna (focal length of the lens).

The satellite antennas are divided into four subsystems. The first supports the links between the satellite and mobile terminals (MTSLs) and links between the fixed terminals and satellites (FSLs). Insatellite links between one satellite S and eight of its neighbors in nearby orbits are shown schematically in Figure 9. Unlike personal terminals, which include portable and mobile phones, the term fixed terminals refers to terminals that are installed in fixed locations. The Fixed Terminal/Satellite link is substantially similar to the Mobile Terminal/Satellite link. Similar but more powerful satellite antennas are used. The FSLs use a different frequency allocation and employ separate paging, calling, and assignment channels.

The second antenna subsystem supports the links between the satellite and gateways (GSLs), and includes eight electronically steerable arrays pointed towards the Earth. The third antenna subsystem supports the links among the satellites (ISLs), and includes a band of electronically steerable antennas around the circumference of the satellite. The fourth antenna subsystem consists of an Earth coverage antenna for the satellite GSL, FTSL, and PTSL pilot tone. The gateways G are the interfaces between the present invention and public telephone networks. They are dedicated fixed sites consisting of two antenna subsystems separated by 30 to 50 km. Figure 10 shows the basic design of a gateway G, and also shows portable P, mobile M and fixed F terminals. Gateways G provide network services such as billing, network database, administration, maintenance, and satellite operations. The GSL uplink uses the 27.5 to 29.5 GHz band and the downlink uses the 17.7 to 19.7 GHz band.

In one embodiment of the invention, each inter-satellite link channel provides a communication capacity of 170 MBPS using 32-CROSS modulation and rate 4/5 coding. The channel density is 1 ISL channel per 51 MHz. Each satellite can support up to 8 ISLs simultaneously and each ISL can support up to 12 duplex ISL channels. The required frequency allocation is 1,224 MHz. Spatial diversity allows all satellites to share the same allocation (100% reuse). The ISL antennas provide 35 to 50 dB gain and autotrack. The nominal transmit power is 0.5 W. The ISLs use the 59 to 64 GHz band. The GSL and ISL bandwidth can be reused 100% from satellite to satellite because of the small antenna beamwidths. The MTSL and FTSL bandwidth can be re-used 100% from Earth fixed cell to Earth fixed cell because of the TDMA scanning pattern.

Figures 11, 12 and 13 supply views of a second alternative satellite design called *Gearsat*™ that may be utilized in concert with the present invention. This spacecraft comprises an inflatable torus. When viewed from the side along its circumference, the torus looks like two flattened pyramids that share a common base. In Figure 12, the reference character MN indicates the height of a man compared to the size of the spacecraft. Phased array antenna panels are deployed across the top of the pyramid, while arrays of amorphous silicon solar cells cover the slanted surfaces. The satellite rotates about its center, and individual portions of the antenna panels are specifically dedicated to transmit and receive signals from pre-defined regions on the surface of the Earth E.

The Superconducting Array

Figure 14 is a schematic diagram that reveals the elements comprising one specific embodiment of a superconducting millimeter wave array 10 that may be employed in combination with the satellite antennas A described above. As is the case with most of the other drawing figures that show the structure of the array 10, the reader should note that the drawings that accompany this specification are not intended to present the invention in its proper scale. These figures are intended to portray the geometric relationships of the various elements of one of the preferred embodiments of the invention. Specific information concerning the basic scale and dimensions of the elements of the invention would be well known to persons skilled in the electronic arts. In the description that follows, terms such as "left", "right", "adjacent", and "atop" are used to assist the reader understand the geometry of the individual structures which comprise the present invention. These terms are used only to help the reader better comprehend the drawings that accompany the specification, and are not intended to limit the disclosure or the scope of the claims that follow.

The superconducting millimeter wave intersatellite link array 10 exhibited in Figure 14 is coupled to transmit (Tx) and receive (Rx) circuitry 12 through a feed coupler 14 that extends into a metal cryogenic envelope 16. The envelope 16 is designed to provide the maximum thermal isolation of the array 10 from the environment outside the envelope 16. One portion of the cryogenic envelope 16 is fitted with a sheet of glass 17 which is coated with a dielectric material. This sheet of glass 17 is located

at the end of the envelope 16 that is opposite to the feed coupler 14. The glass 17 is generally transparent to allow microwave radiation to pass in and out of the envelope 16 as it journeys to and from other satellites in the constellation. The feed coupler 14 introduces a low loss signal feed 18 into the interior of the cryogenic envelope 16. One good choice of material for the feed coupler 14 is a silica aerogel known as "Frozen Smoke", which provides adequate mechanical strength, is extremely light weight, and also exhibits a very low thermal conductivity. This feed 18 passes through a chamber or reservoir 19 that is defined by the inside walls of the envelope 16 and one surface of an array substrate 20. The reservoir 19 is filled with a cryogenic coolant. The space within the envelope 16 opposite the cryogenic reservoir 19 is held at or near a vacuum to minimize heat exchange. In one embodiment of the invention, liquid nitrogen fills chamber 19, and the array substrate 20 is fabricated from sapphire. The material chosen for the array substrate 20 should be an insulator which can be machined. A support 21 holds the substrate 20 within the envelope 16. In the preferred embodiment of the invention, support 21 is an annular structure that can be altered or reduced in size by automatic or remote command once the satellite S has achieved its position in orbit. A copper tungsten alloy which has a coefficient of thermal expansion that matches sapphire is a good selection of material for support 21. The sapphire substrate 20 contains an embedded conductive ground plane 22.

In Figure 14, the ISL beam that communicates with other satellites is indicated by the arrow labeled "ISL". The reference characters IRI and IRR delineate incident and reflected infra-red radiation.

A superconducting microstrip series feed layer 24 resides atop the substrate 20 on the side opposite the feed coupler 14. The superconducting layer 24 may be formed from any number of high temperature superconducting materials (HTSC), but $YBa_2Cu_30_7$-Δ has been designated for one of the preferred embodiments. The low surface resistance of the superconducting layer 24 keeps losses within the array 10 to a minimum. During the manufacturing process, a complete superconducting layer 24 can be deposited over substrate 20 using conventional MOCVD (metal-oxide chemical vapor deposition) processes. A portion of the layer 24 is then etched away to form the microstrip array of cascaded power dividers that is depicted in Figure 15. The entire superconducting layer 24 is coupled to the signal feed 18 at the center of the microstrip array. Radiating microstrip traces end in terminals 25. The superconducting layer 24 is thermally isolated from the rest of the array 10 by a heat reflecting coated dielectric layer 26. The heat reflecting coated dielectric layer 26 keeps visible, infrared and ultraviolet radiation away from the superconducting layer 24, while allowing microwave and millimeter wave radiation to pass through it. A slotted conductive ground plane 27 resides next to layer 26. The ground plane 27 is perforated with a pattern of rectangular slots, and are identified in Figures 15 and 18 as 29. Each rectangular slot 29 on the ground plane 27 is aligned over a microstrip terminal 25 on the superconducting layer 24.

A layer of conductive radiating elements 30 attached to a Kapton™ backing 28 is deployed to the right of the slotted ground plane 27 in Figure 14. Each individual conductive element 31 is made from

a metal such as copper, and is carefully positioned to register with one of the microstrip terminals 25 on the superconducting layer 24 and with one of the slots 29 on the slotted ground plane 27. This registration pattern is best seen in Figure 18. The conductive elements 31 are electrostatically coupled to the superconducting feed network 24, and experience ambient temperature, as opposed to the chilled 77 degree Kelvin environment that embraces the superconductor portion of the array 10. Spacer layers 32 formed from "Frozen Smoke" silica aerogel separate the layer of conductive radiating elements 30 from a bandwidth-expanding parasitic element layer 34. The individual conducting patches 35 are also positioned to line up with terminals 25, slots 29, and conductive radiating elements 31. Additional spacer layers 32 separate polarizing layers 36 and a dielectric mirror 38 as shown in Figure 14.

Figure 15 provides a top view of the superconducting microstrip layer 24 that is shown in side view in Figure 14. Figure 16 illustrates an enlarged portion D of Figure 15 which shows the alignment of microstrip terminals 25, slots 29, and conductive radiating elements 31. Figure 17 illustrates a 32 by 32 array comprising a plurality of conductive radiating elements 31. Figure 18 depicts the relative positions of the terminals 25 on the superconducting microstrip layer 24 depicted in Figure 15, the slots 29 on the ground plane layer 27, and the conductive radiating elements 31 shown in Figure 17.

A signal waveguide 42 comprising a thin metal layer 44 enclosing a dielectric 46, a cryogenic heat pipe 48, and a conduit 50 for power and control wiring passing through the cryogenic envelope 16 are pictured in Figure 19.

Details of the construction of a heat pipe subassembly 52 within the sapphire substrate 20 are supplied by Figures 20 and 21. The substrate 20 comprises two sections that are glued together after one section has been machined to form a series of rectangular grooves 54. These grooves 54 are capable of receiving a wick 56 that is connected to a bulb 58. The bulb 58 is thermally coupled to a cryogenic heat pipe 60 that is located near the edge of the sapphire substrate 20 that contains the bulb 58.

Figure 22 exhibits the coupling of optical fibers 62 through a transmissive dielectric material 64. Figure 23 presents a schematic view of optical fibers 62 that deliver photons 66 to layers 70 which absorb optical energy. These layers 70 are located on the superconducting layer and control the operation of the array 10. Figure 24 depicts the layout of a superconducting flux flow transistor (SFFT) 71, which comprises a control line 72, two masses of superconducting material 74 and 76 and weak links 78.

Figure 25 shows the details of the electronic time delay steering. The switched line lengths in the feed network are used to generate a "stairstep" time delay envelope. Low cost SFFT variable time delay networks are used at each radiating element to provide fine grain delay necessary for efficient antenna performance and low sidelobe levels. Figure 26 shows the architectural difference between an active element array, which is necessary when the beamforming feed network suffers from high losses, and a semi-active array where feed losses are low and the only active components at the antenna element are low loss variable time delay networks. The HTSC low loss feed and low loss switch enable this

architecture which provides most of the cost reduction for the present invention compared to previous systems.

The embodiment of the array 10 shown in Figure 14 is designed to be housed in a package that is approximately 5" x 20" x 2.5" (12.5 cm x 50 cm x 6.25 cm) and weighs 5.5 (2.5 kg) pounds. The unit will require 12 watts to 48 watts of power (500 MHz to 2 GHz bandwidth) and uses 0.75 watt of cryogenic cooling. The cooling can be generated with a 0.5 square meter passive radiator directed at cold space, or with an active cryogenic cooler powered with 18 watts DC. The power amplifier is located outside the cryogenic envelope 16. In comparison, a conventional millimeter wave system would have a volume of approximately 8" x 8" x 5" (20 cm x 20 cm x 12.5 cm), would weigh approximately 15 pounds, and would use roughly from 100 watts to 400 watts (for 500 MHz to 2 GHz bandwidth).

Figure 27 reveals the satellite design 80 called *Callingsat*™ that is utilized to implement the most preferred embodiment of the invention. *Callingsat*™ 80 comprises a central octagonal panel 82, eight radiating arms 84, intersatellite link antennas 86, and extendable mast 88, and an array of solar panels 90 that shades the body of the satellite 80 from solar radiation. Figure 28 depicts the "underside" of *Callingsat*™ 80 as viewed from the Earth E. The octagonal panel 82 and each radiating arm 84 carries transmit and receive antennas 92 and 94, respectively, which are best illustrated in Figure 29.

CONCLUSION

Although the present invention has been described in detail with reference to a particular preferred embodiment, persons possessing ordinary skill in the art to which this invention pertains will appreciate that various modifications and enhancements may be made without departing from the spirit and scope of the claims that follow. The various orbital parameters and satellite population and configuration statistics that have been disclosed above are intended to educate the reader about various preferred embodiments, and are not intended to constrain the limits of the invention or the scope of the claims. Similarly, although the preferred embodiments have been described as using particular materials, many substitutions and equivalents could be utilized without departing from the essence of the invention. The List of Reference Numerals which follows is intended to provide the reader with a convenient means of identifying elements of the invention in the specification and drawings. This list is not intended to delineate or narrow the scope of the claims.

INDUSTRIAL APPLICABILITY

The *Spacecraft Intersatellite Link for Satellite Communication System* described above will help to overcome the limits that circumscribe the performance of existing telephone systems. The present invention is capable of offering continuous voice, data and video service to customers across the globe on the land, on the sea, or in the air. Instead of merely improving upon or expanding existing land-based systems, the present invention bypasses centralized terrestrial switching hardware by placing all

the intelligence of the network in orbit. Unlike conventional hierarchical systems, which are linked together by a complex web of wires, cables, glass fibers, and microwave repeaters that are very expensive to build and maintain, the present invention liberates the true communications potential of existing land-based networks by routing signals through spacecraft in low Earth orbit. The present invention will revolutionize the telecommunications industry, and offer a wide spectrum of services and industrial opportunities around the world.

LIST OF REFERENCE CHARACTERS

Figures 1, 2, 3, & 5

A	Spacecraft Antennas
B	Beams
H	Hexagonal facets
E	Earth
SP	Solar panels
S	Satellite
T	Beam footprints
Z	Zenith

Figures 6, 7 & 8

AF	Array face
AL	Active lens
FD	Feed
RE	Radiating elements
SW	Switch
TDAL	Time delay active lens
TDN	Time delay network
TDP	Time delay path
TL	Transmission line

Figure 10

F	Fixed terminal
G	Gateway
M	Mobile terminal
P	Portable terminal

Figures 11, 12 & 13

A	Antennas
MN	Man

Figures 14 through 23

10	Superconducting millimeter wave Intersatellite Link Array
12	Transmit (Tx) and Receive (Rx) Circuitry
14	Feed coupler
16	Cryogenic envelope
17	Microwave transparent glass with dielectric coating
18	Signal feed
19	Cryogenic coolant reservoir
20	Sapphire substrate
21	Copper-tungsten alloy removable support
22	Ground plane
24	Superconducting microstrip series feed layer
25	Microstrip terminals
26	Heat reflecting coated dielectric layer
27	Slotted ground plane
28	Kapton™ backing
29	Individual slot
30	Layer of conductive radiating elements
31	Individual radiating element
32	Spacer layers
34	Bandwidth-expanding parasitic layer
35	Individual conducting parasitic patch
36	Polarizing layers
38	Dielectric mirror
42	Signal waveguide
44	Thin metal layer
46	Dielectric
48	Cryogenic heat pipe
50	Conduit for power and control wiring
52	Heat pipe subassembly
54	Rectangular grooves
56	Wick

58 Bulb
60 Cryogenic heat pipe
62 Optical fiber
64 Transmissive dielectric material
66 Photons
70 Optical energy absorbing layers
D Detail
ISL Intersatellite link beam
IRI Incident infra-red radiation
IRR Reflected infra-red radiation

Figure 24

71 Superconducting flux flow transistor
72 Control line
74 First Superconductor
76 Second Superconductor
78 Weak links

Figures 27, 28 & 29

80 *Callingsat*™
82 Central octagonal panel
84 Radiating arms
86 ISL antennas
88 Mast
90 Solar panels
92 Transmit antennas
94 Receive antennas

CLAIMS

What is claimed is:

1. An apparatus for providing a plurality of radiated beams (B) directed toward the Earth's surface (E); said apparatus being capable of communicating directly with a plurality of portable (P), mobile (M), and fixed (F) terminals and gateways (G) comprising:

a plurality of satellites (S); each satellite (S) including

a plurality of antennas (A);

each of said plurality of antennas (A) being capable of simultaneously generating said plurality of radiated beams (B) which are electronically steered; and

an intersatellite link antenna (A, 86)

said intersatellite link antenna (A, 86) including

a superconducting millimeter wave array (10).

2. A superconducting millimeter wave array (10) comprising:

a cryogenic envelope (16); said cryogenic envelope having a portion (17) that is substantially transparent to microwave radiation; said cryogenic envelope (16) also having and defining a cryogenic coolant reservoir (19);

a signal feed (18) passing through said cryogenic envelope (16);

a sapphire substrate (20); said sapphire substrate (20) being capable of receiving said signal feed (18); said sapphire substrate (20) including and enveloping a ground plane (22);

an annular support (21) coupled to said sapphire substrate (20) for holding said sapphire substrate (20) inside said cryogenic envelope (16);

a superconducting microstrip series feed layer (24) which emits electromagnetic radiation; said superconducting microstrip series feed layer (24) being deposited and etched atop said sapphire substrate (20); said superconducting microstrip series feed layer (24) including a plurality of microstrip terminals (25);

a heat reflecting, coated dielectric layer (26); said heat reflecting, coated dielectric layer (26) being adjacent to said superconducting microstrip series feed layer (24);

a slotted ground plane (27); said slotted ground plane (27) being adjacent to said heat reflecting, coated dielectric layer (26); said slotted ground plane having a plurality of slots (29), each slot (29) being generally aligned over each of said plurality of microstrip terminals (25);

a layer of conductive radiating elements (30) having a plurality of conductive radiating elements (31); each of said conductive radiating elements (31) being arranged in a layer positioned next to said slotted ground plane (27) but not touching said slotted ground plane (27); said plurality of conductive radiating elements (31) also being arranged in a pattern in which each of said plurality of conductive radiating elements (31) is positioned over each of said plurality of microstrip terminals (25) on said superconducting microstrip series feed layer (24) and registering with each of said slots (29) in said slotted ground plane (27);

a parasitic patch layer (34); said parasitic patch layer being deployed near said layer of conductive radiating elements (30); said parasitic patch layer (34) including a plurality of parasitic patches (35) positioned to line up with each of said conductive radiating elements (31), each of said slots (29), and each of said microstrip terminals (25);

a polarizing layer (36); said polarizing layer (36) residing adjacent to said parasitic patch layer (34); and

a dielectric mirror (38); said dielectric mirror (38) being deployed near said polarizing layer (36).

3. An apparatus as claimed in Claims 1 and 2, in which said annular support (21) provides firm mechanical coupling during the launch of said satellite (S) and can be substantially reduced in size once said satellite has achieved low Earth orbit.

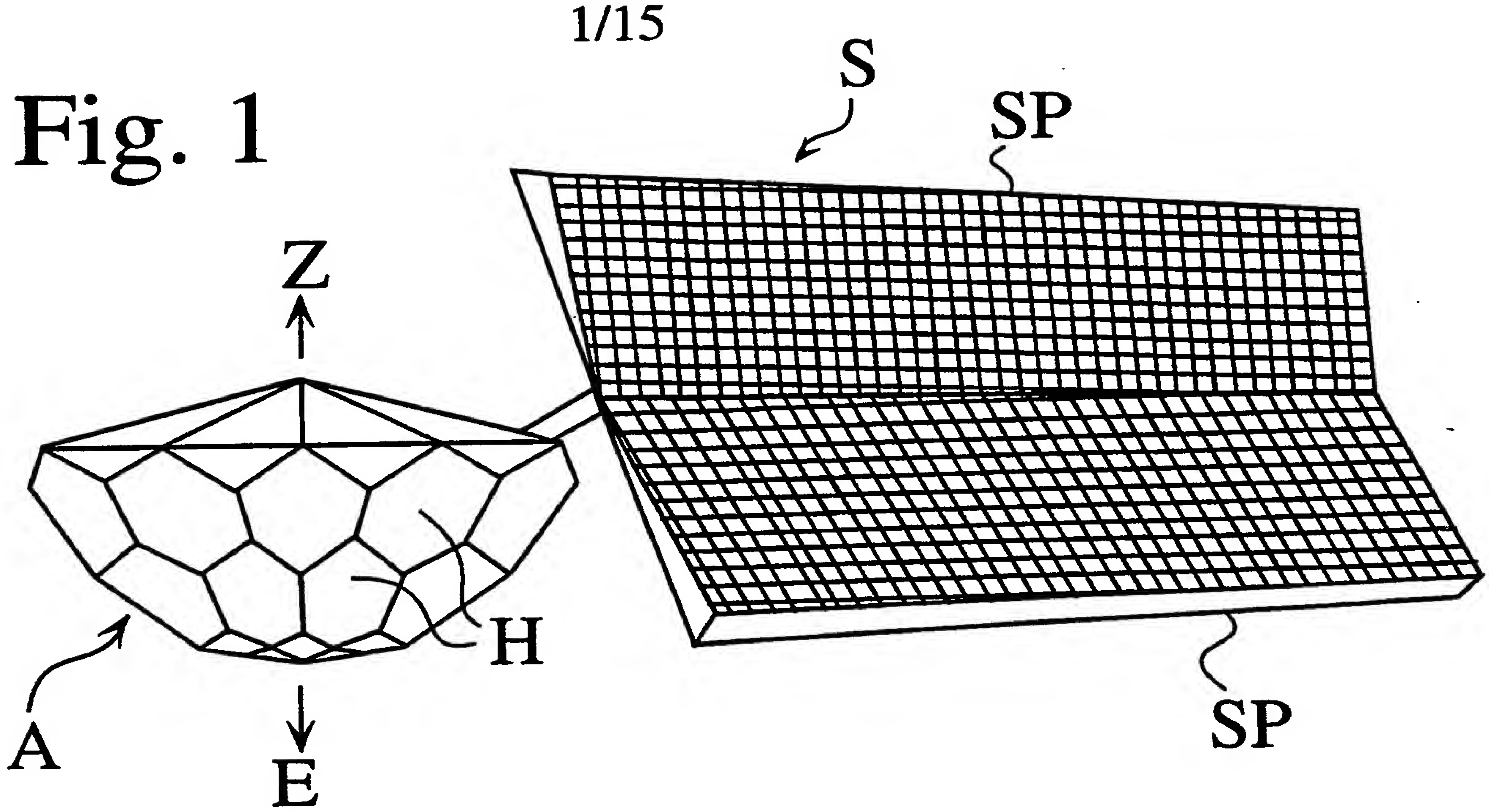
4. An apparatus as claimed in Claim 2, further comprising spacer layers (32) fabricated from a silica aerogel.

5. An apparatus as claimed in Claim 2, in which said sapphire substrate (20) includes an optical fiber (62) which delivers photons to said superconducting microstrip series feed layer (24) to selectively heat particular localized areas of said superconducting microstrip series feed layer (24) to increase the local temperature above the critical temperature of the superconductor causing the superconductor resistance to rise.

6. An apparatus as claimed in Claim 5, in which said optical fiber (62) is coupled through a transmissive dielectric material (64).

7. An apparatus as claimed in Claim 2, in which said sapphire substrate (20) includes a bulb (58) and a wick (56) embedded inside said sapphire substrate (20) and in which said bulb (58) and said wick (56) are thermally coupled to a cryogenic heat pipe (60).

Fig. 1



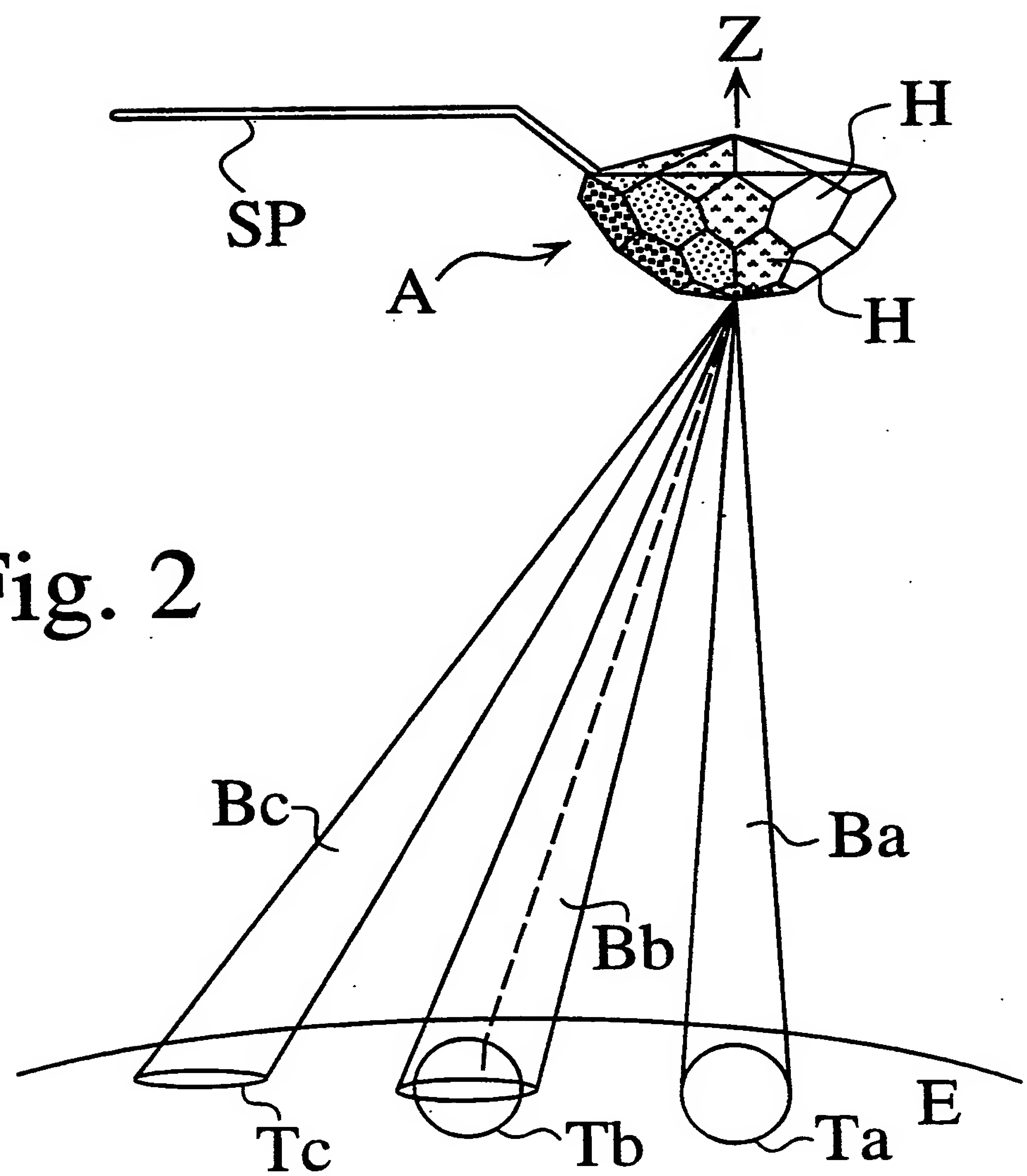
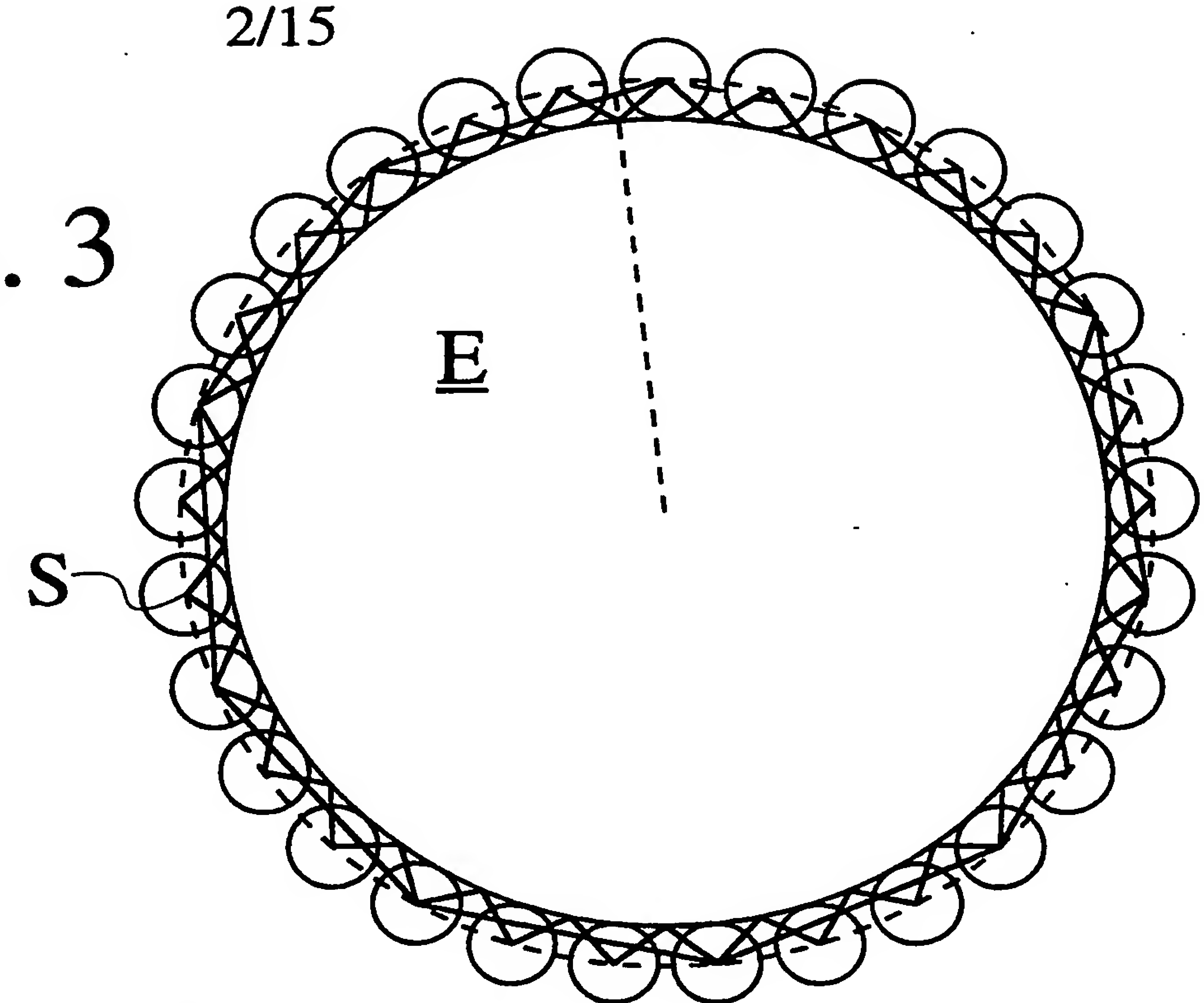


Fig. 2

Fig. 3



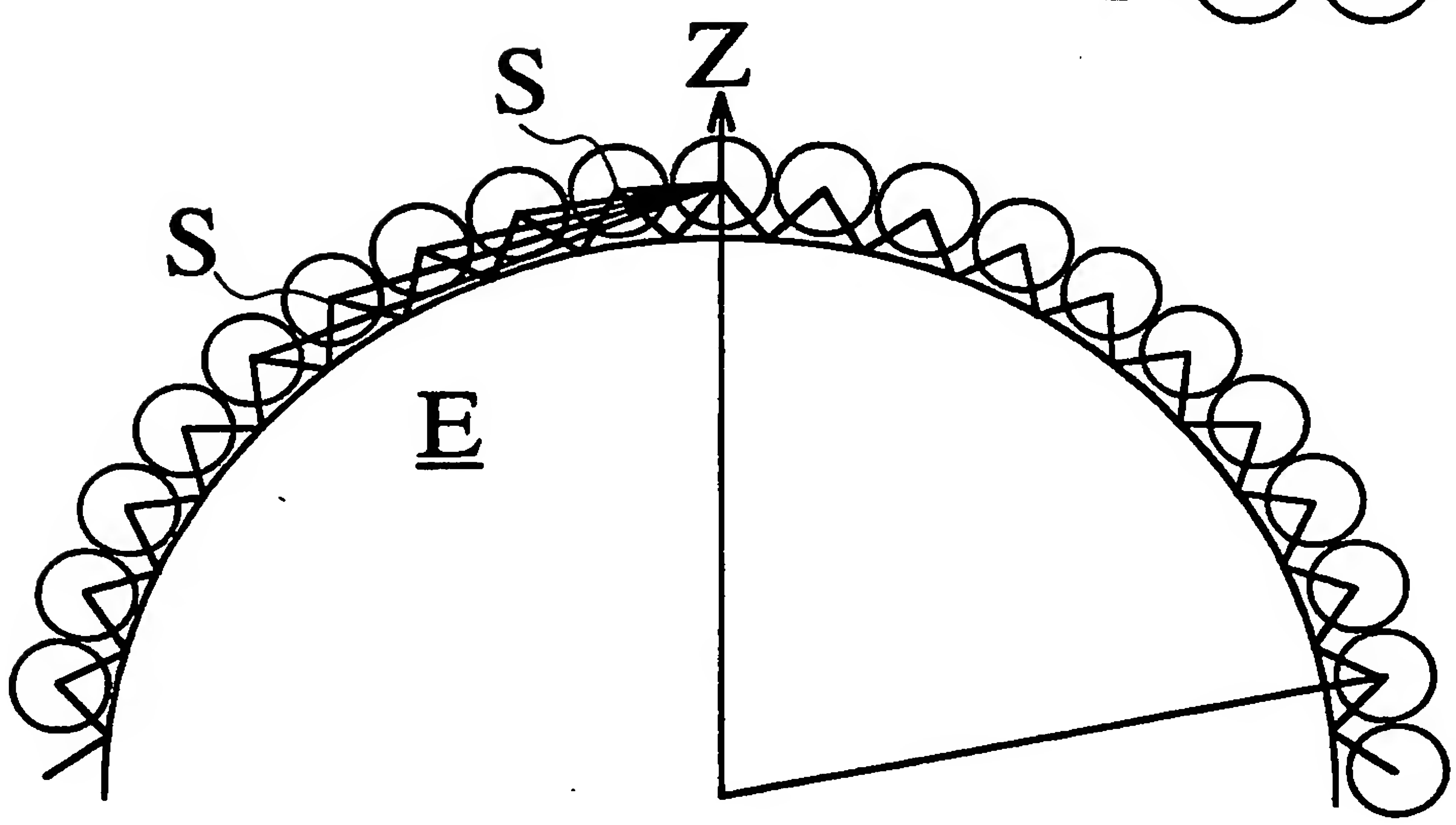


Fig. 4

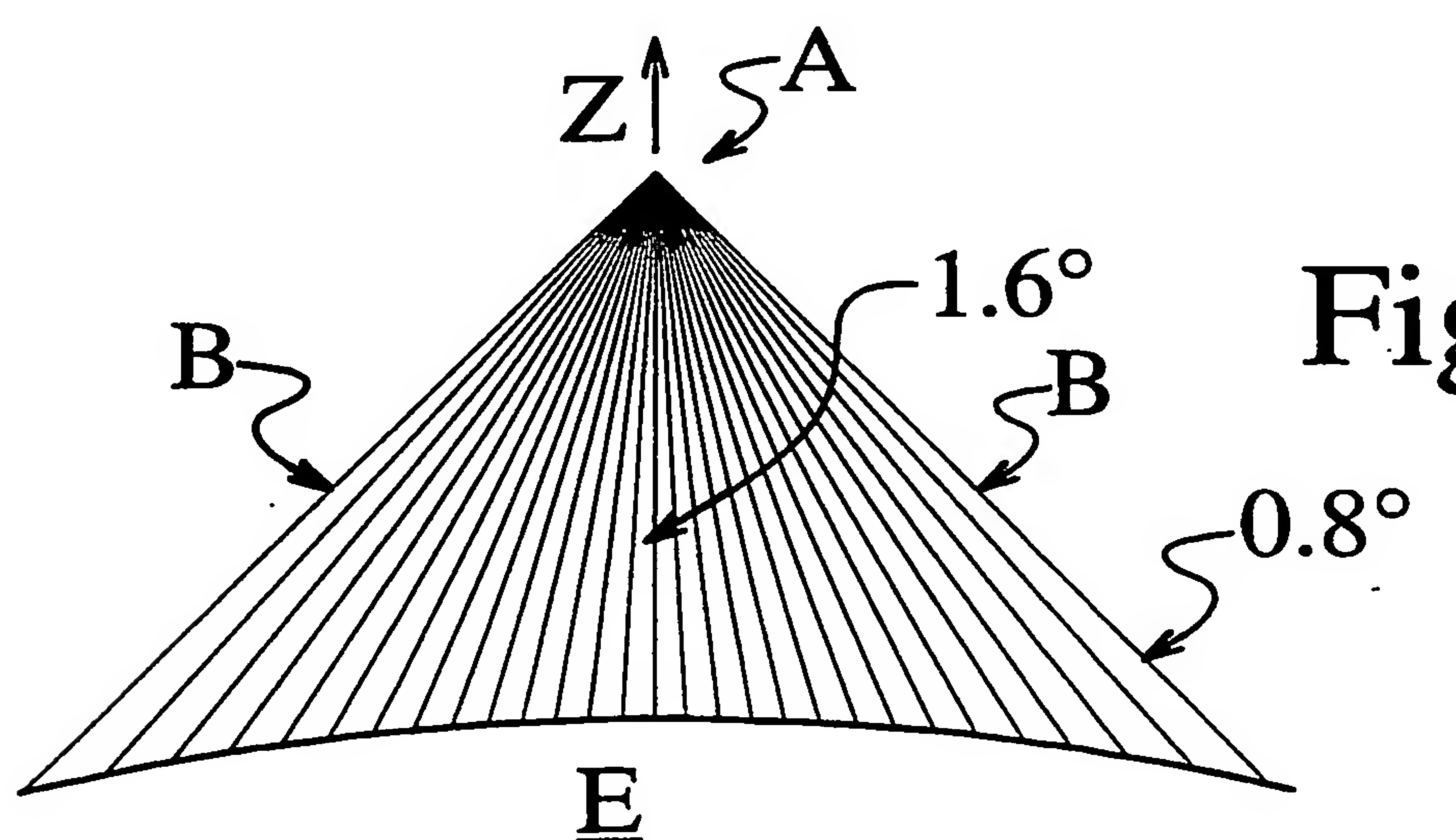
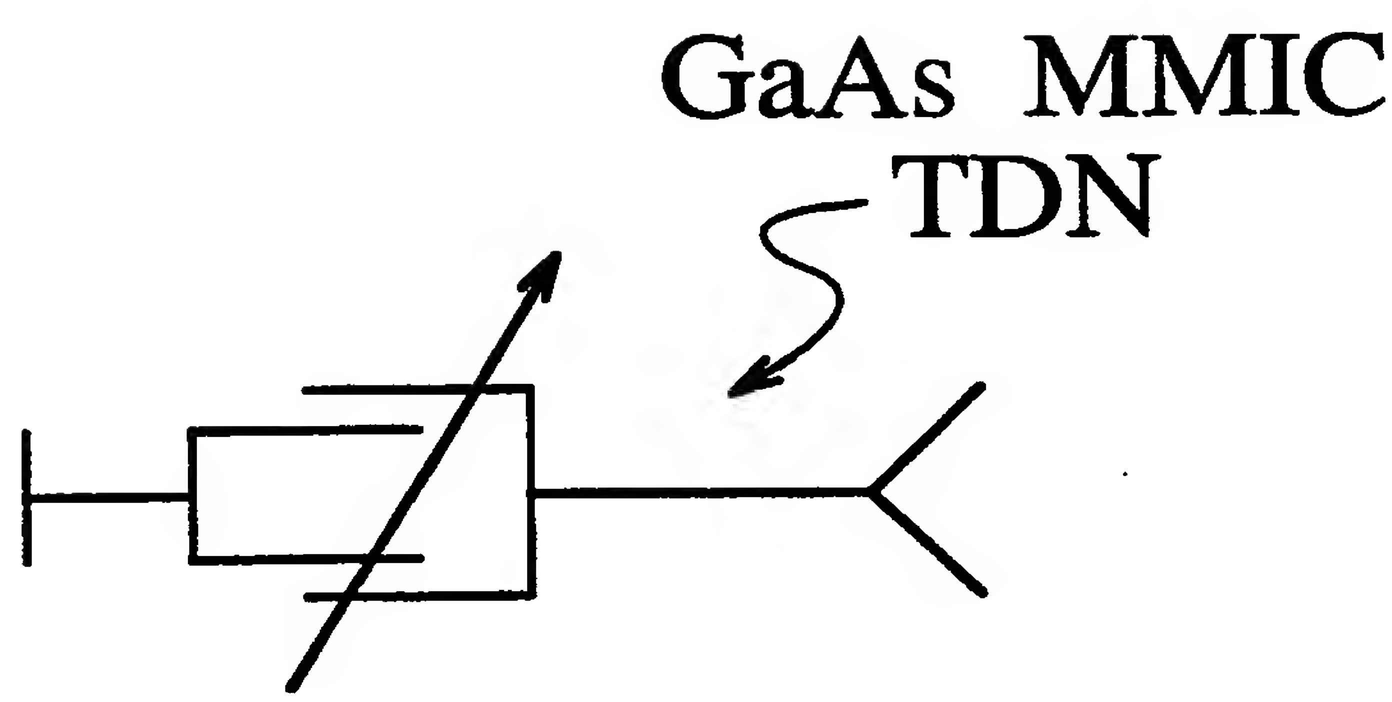


Fig. 5



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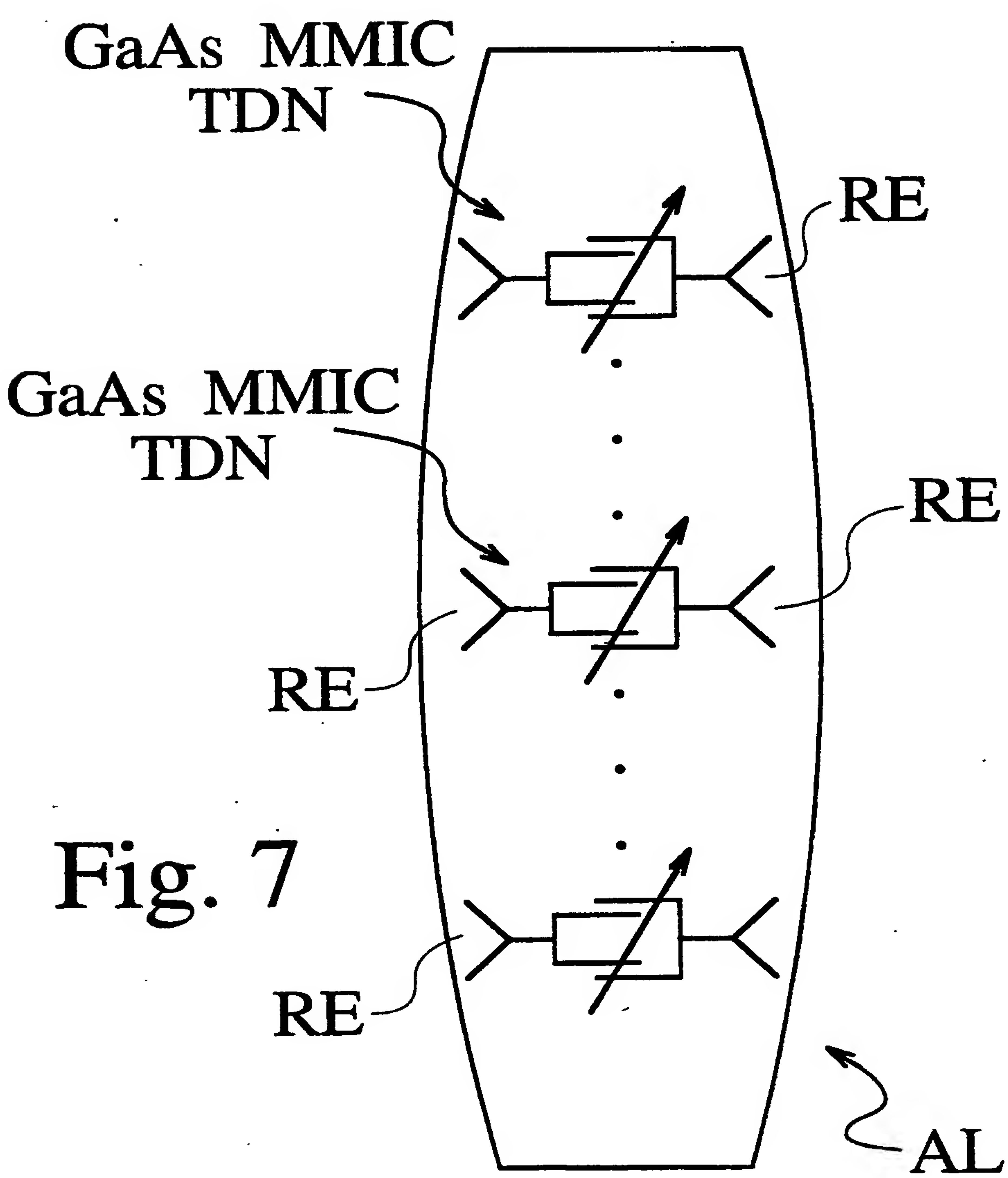


Fig. 7

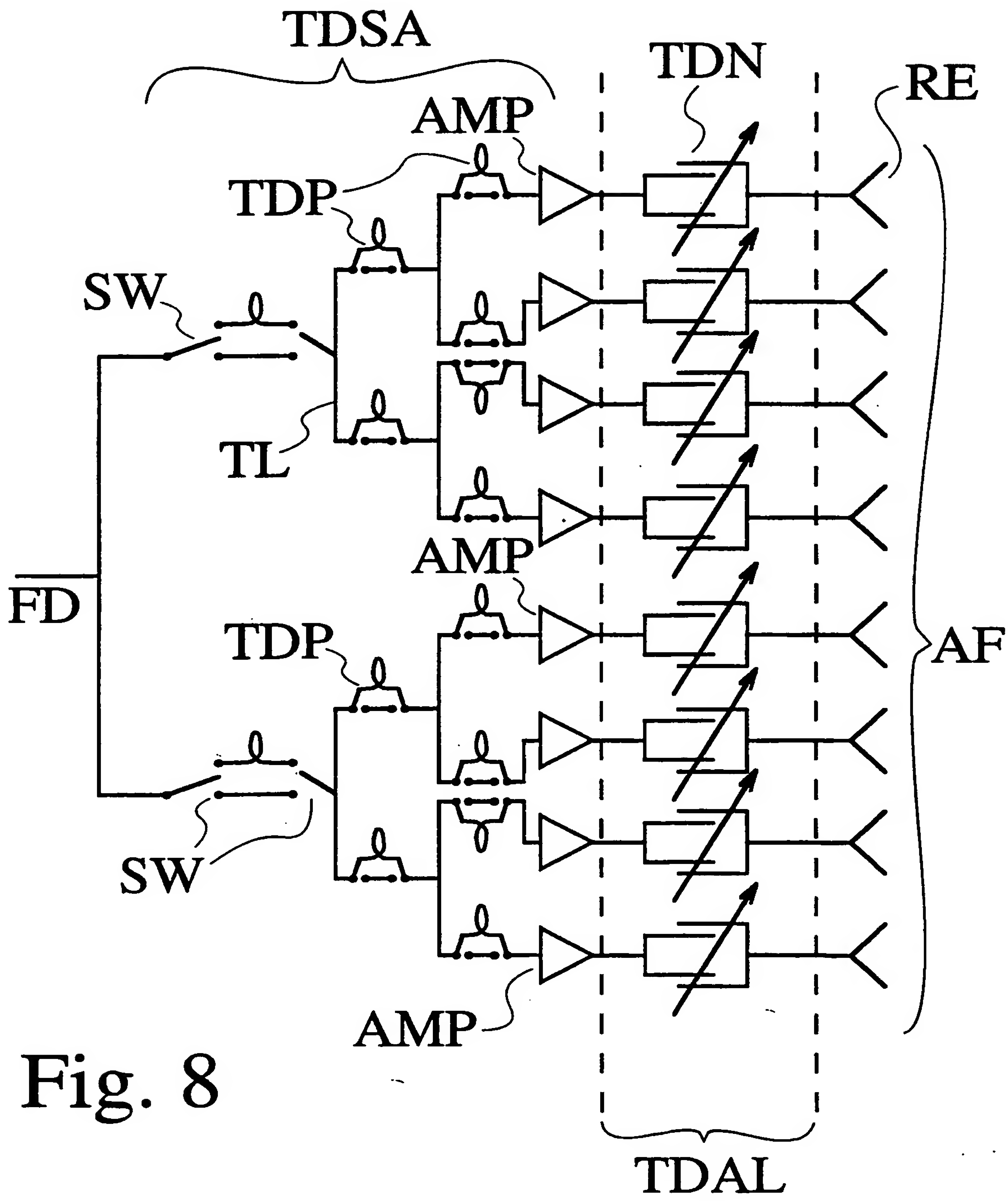


Fig. 8

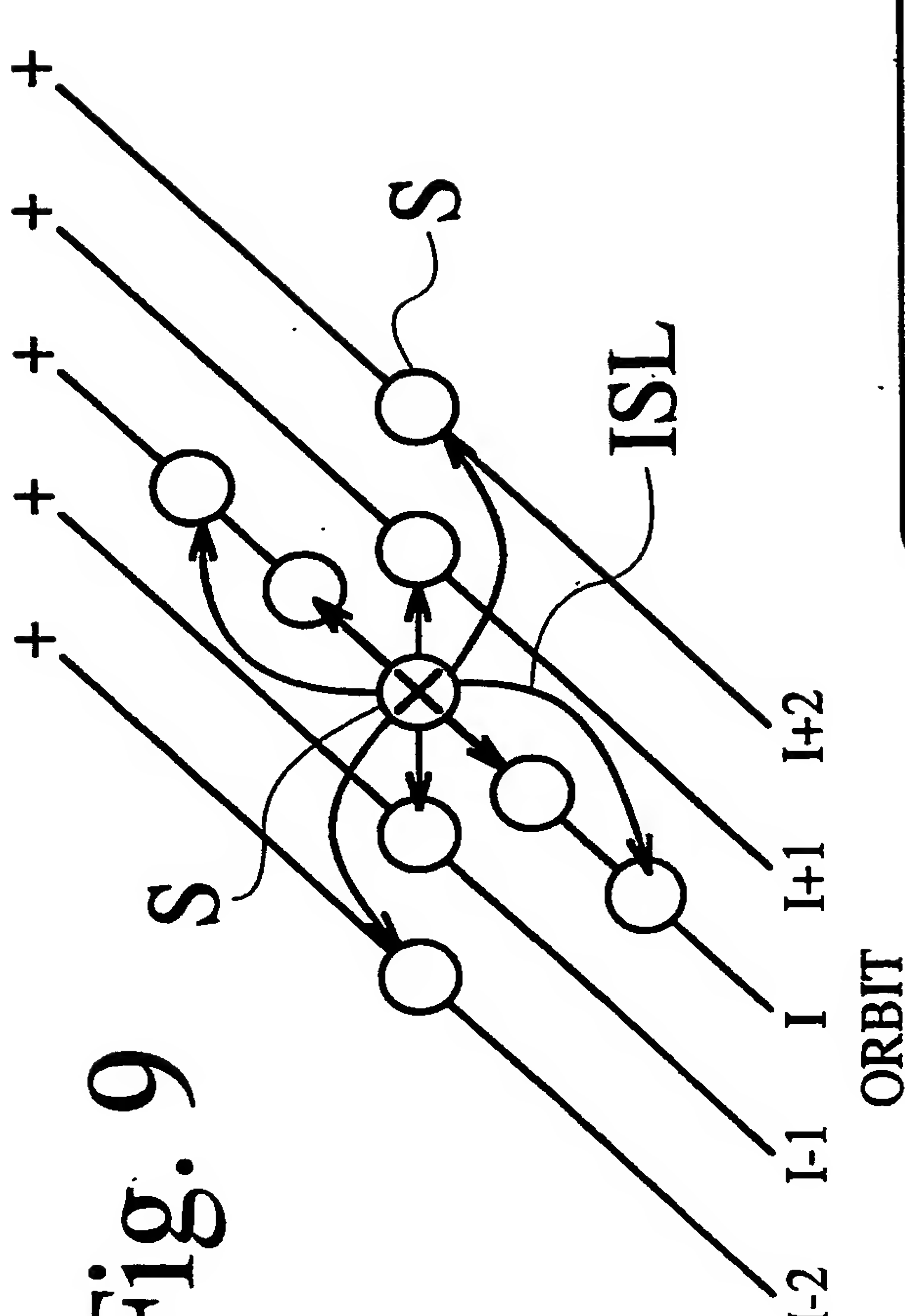

S
S
ISL
I-2
I-1
I
I+1
I+2
ORBIT

Fig. 9

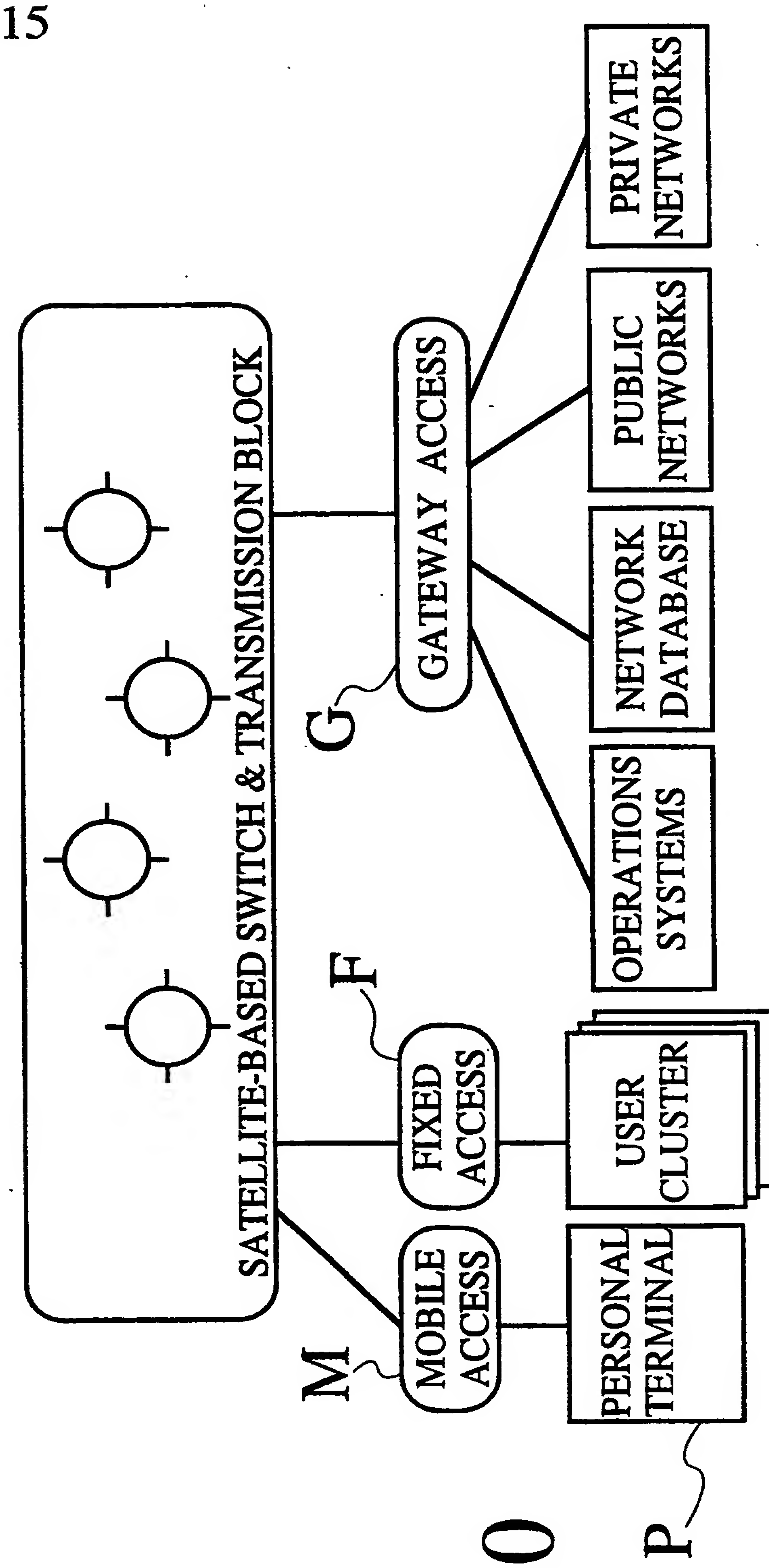

SATELLITE-BASED SWITCH & TRANSMISSION BLOCK
G
GATEWAY ACCESS
F
FIXED ACCESS
M
MOBILE ACCESS
PERSONAL TERMINAL
P
USER CLUSTER
OPERATIONS SYSTEMS
NETWORK DATABASE
PUBLIC NETWORKS
PRIVATE NETWORKS

Fig. 10

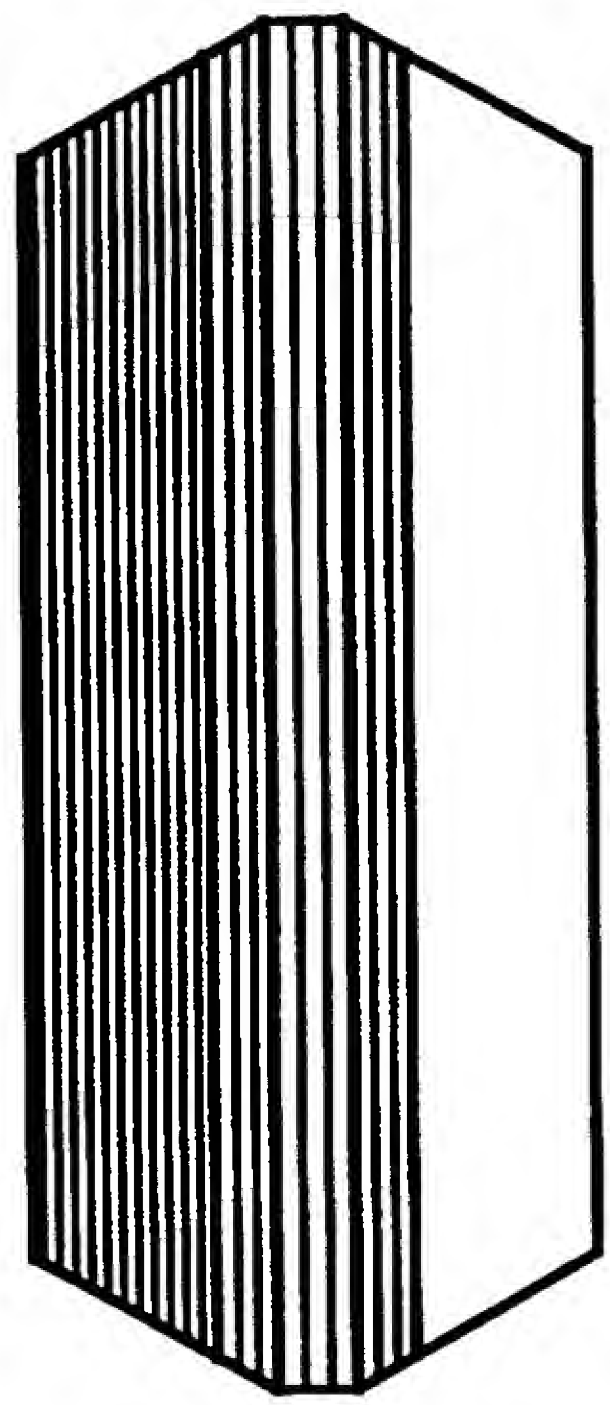


Fig. 11

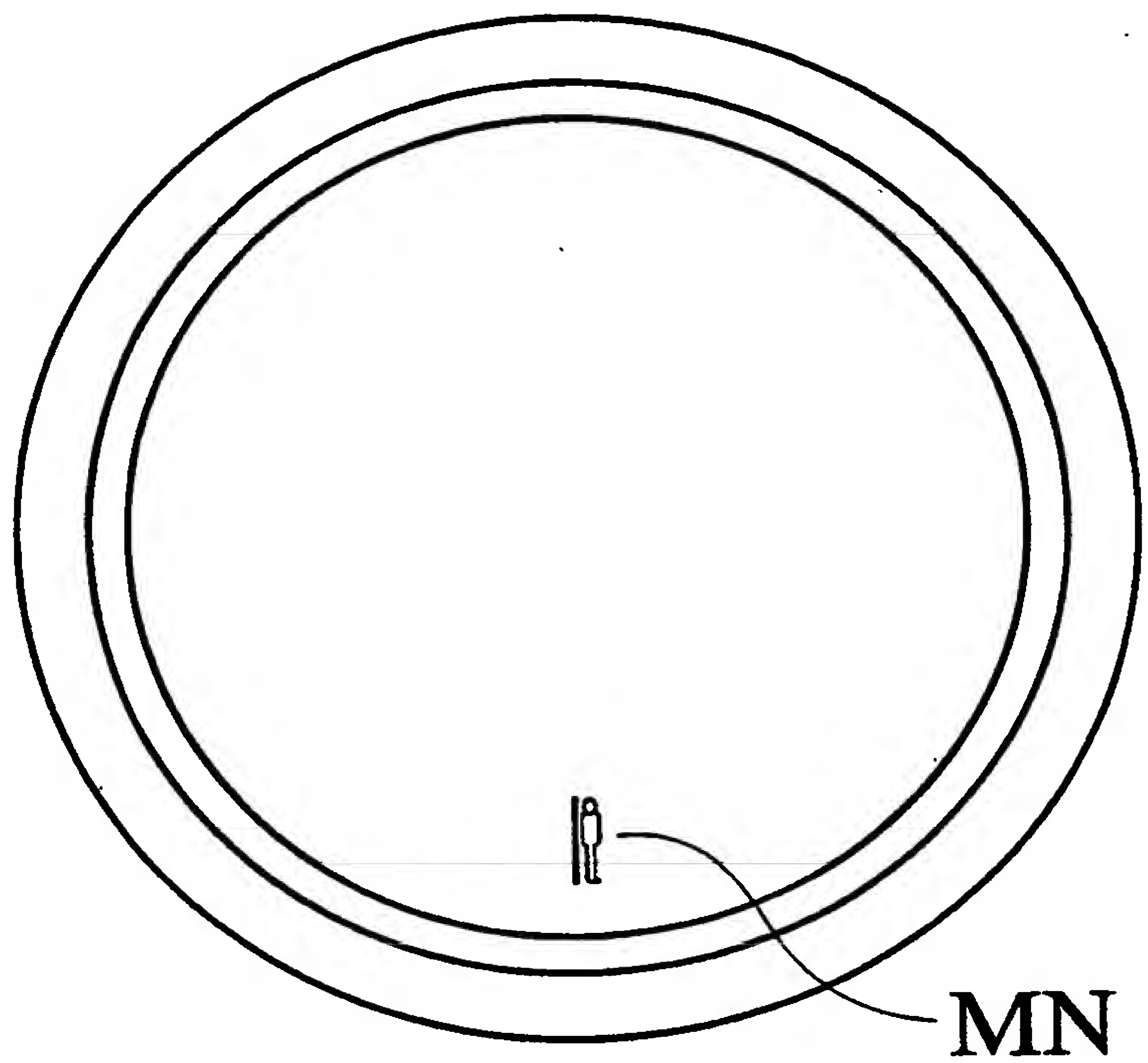


Fig. 12

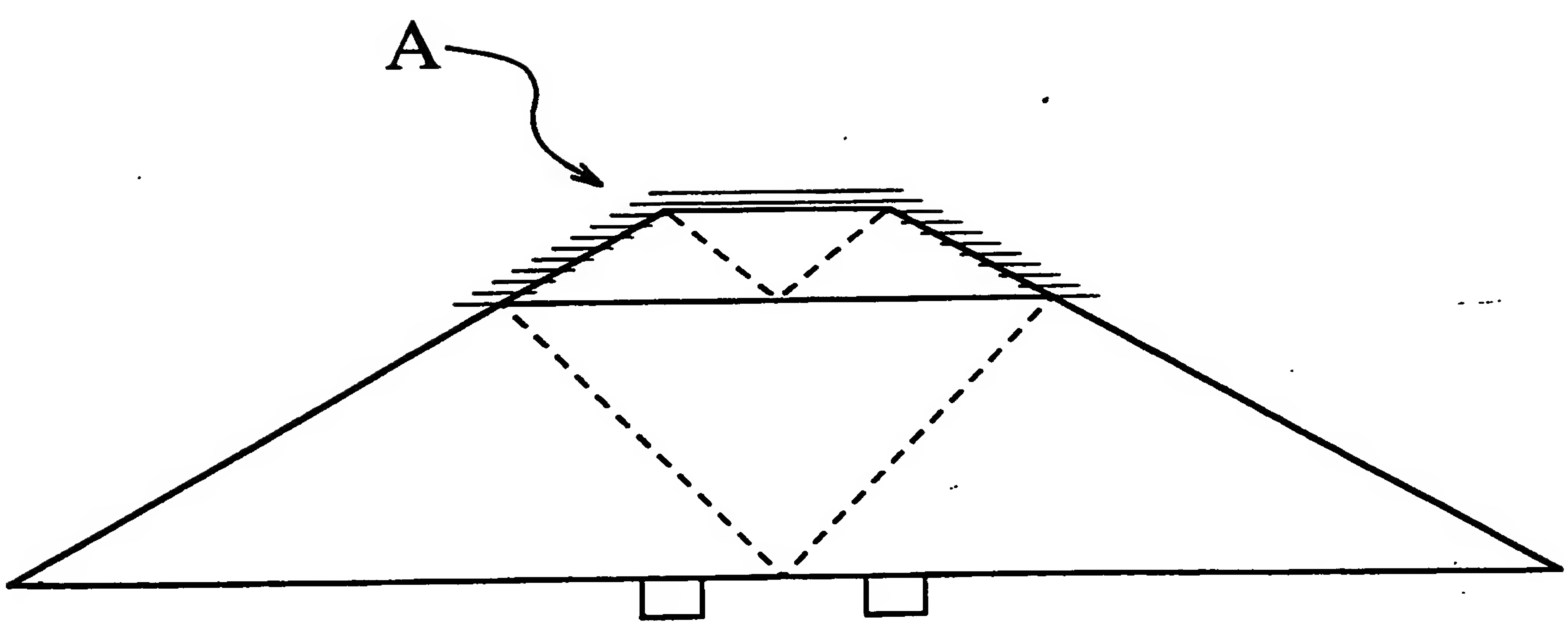


Fig. 13

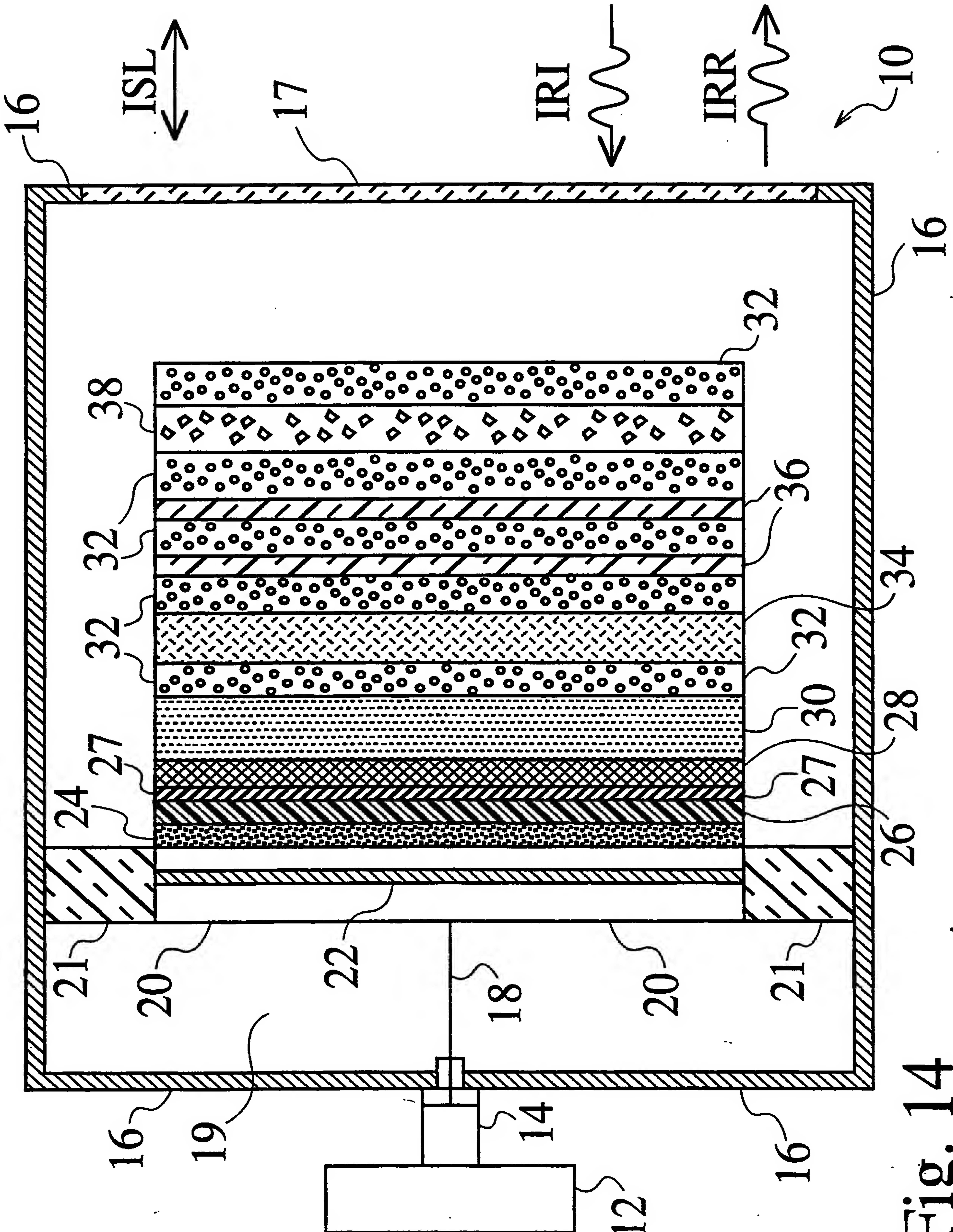


Fig. 14

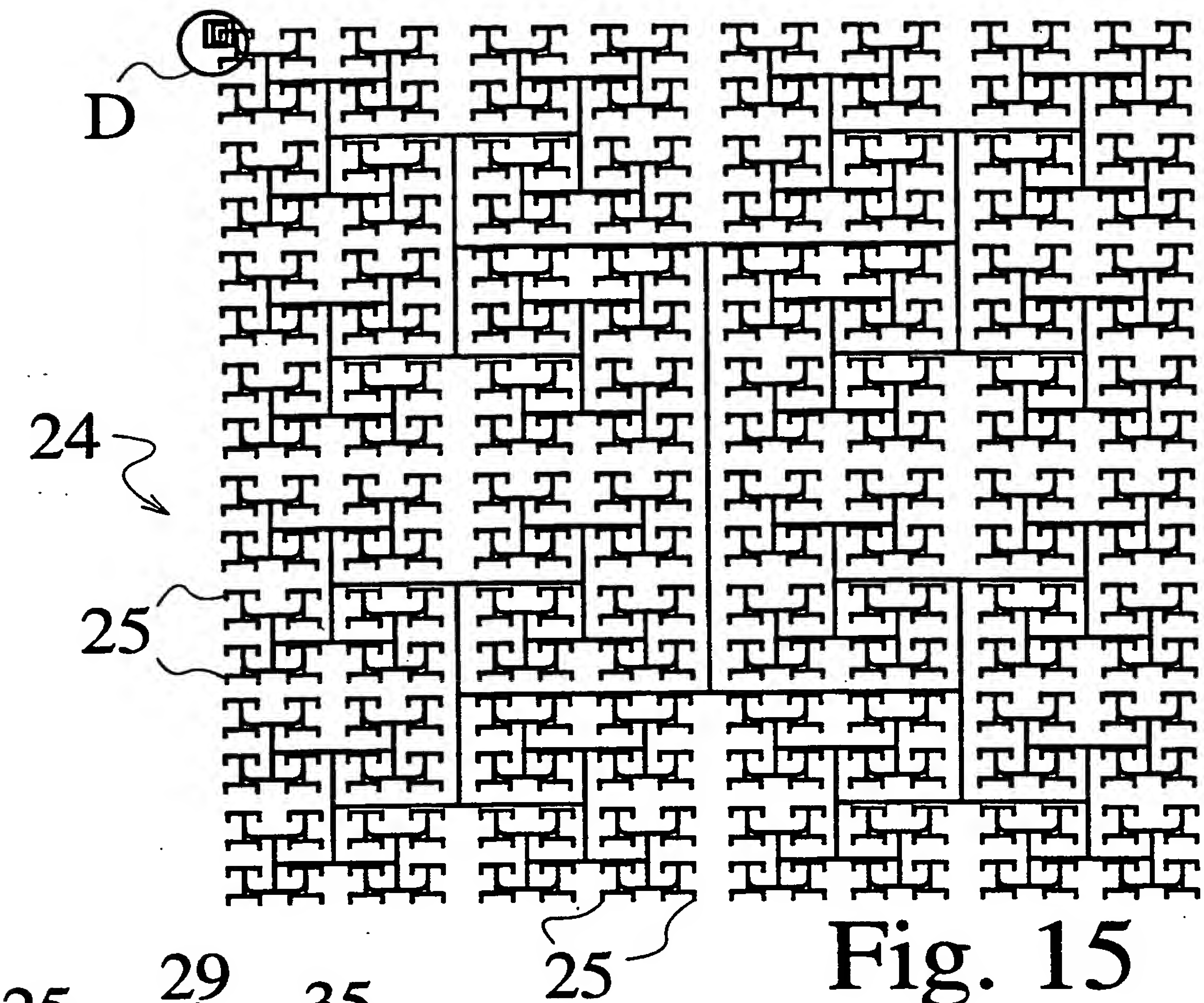


Fig. 15

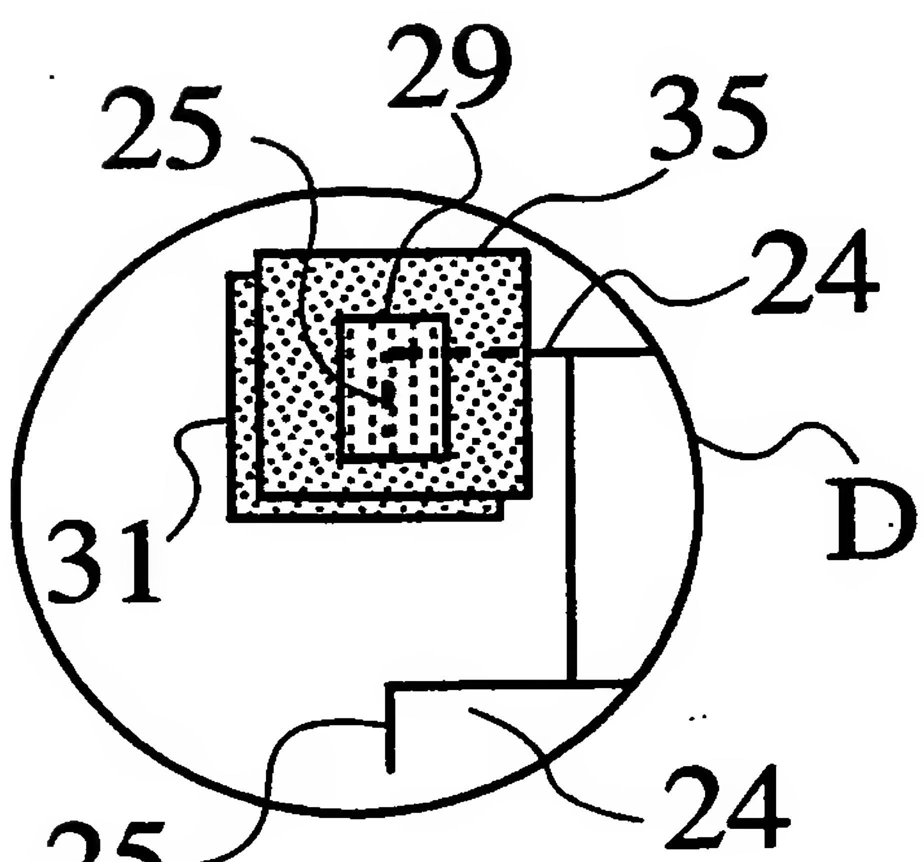


Fig. 16

Fig. 17

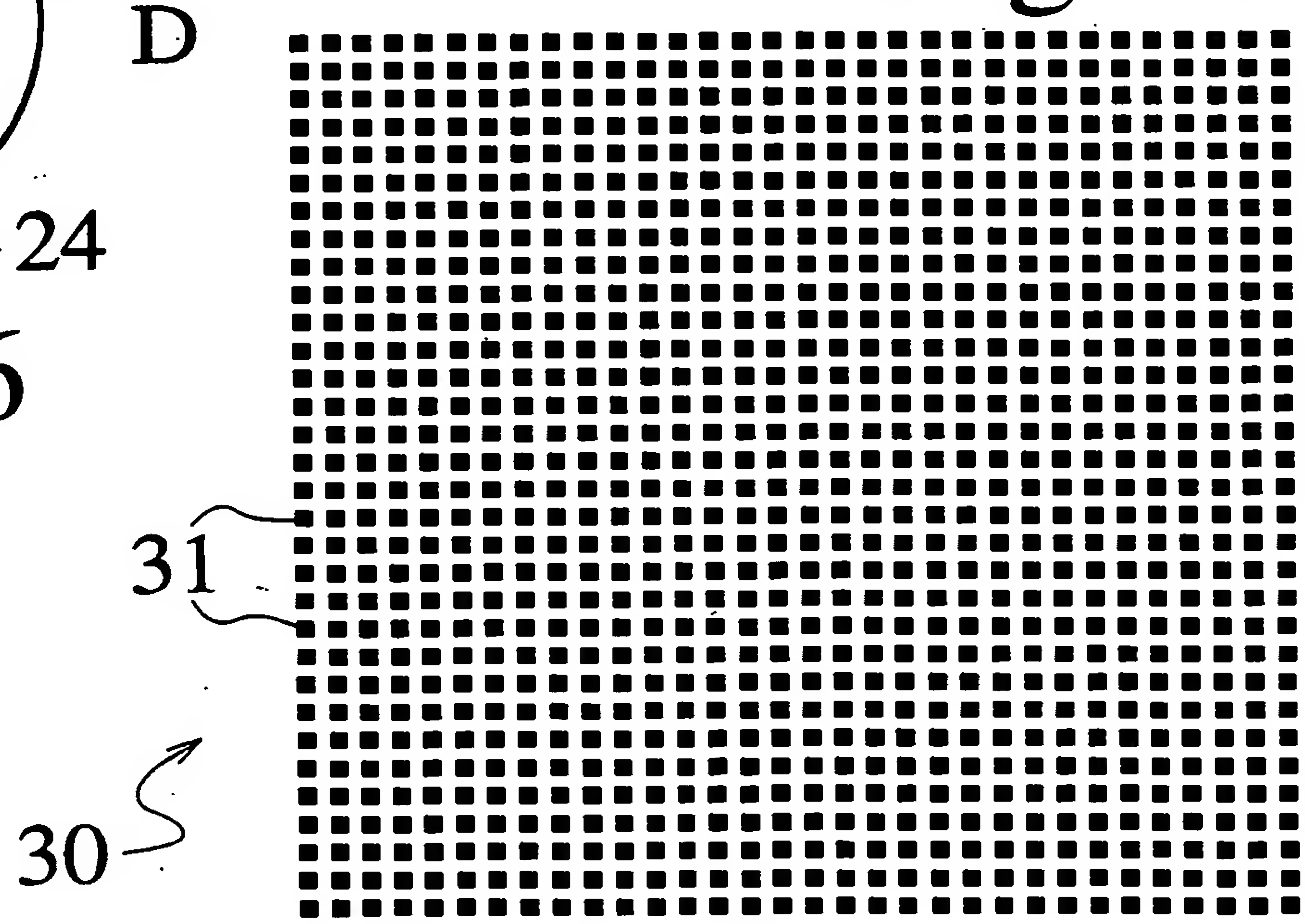
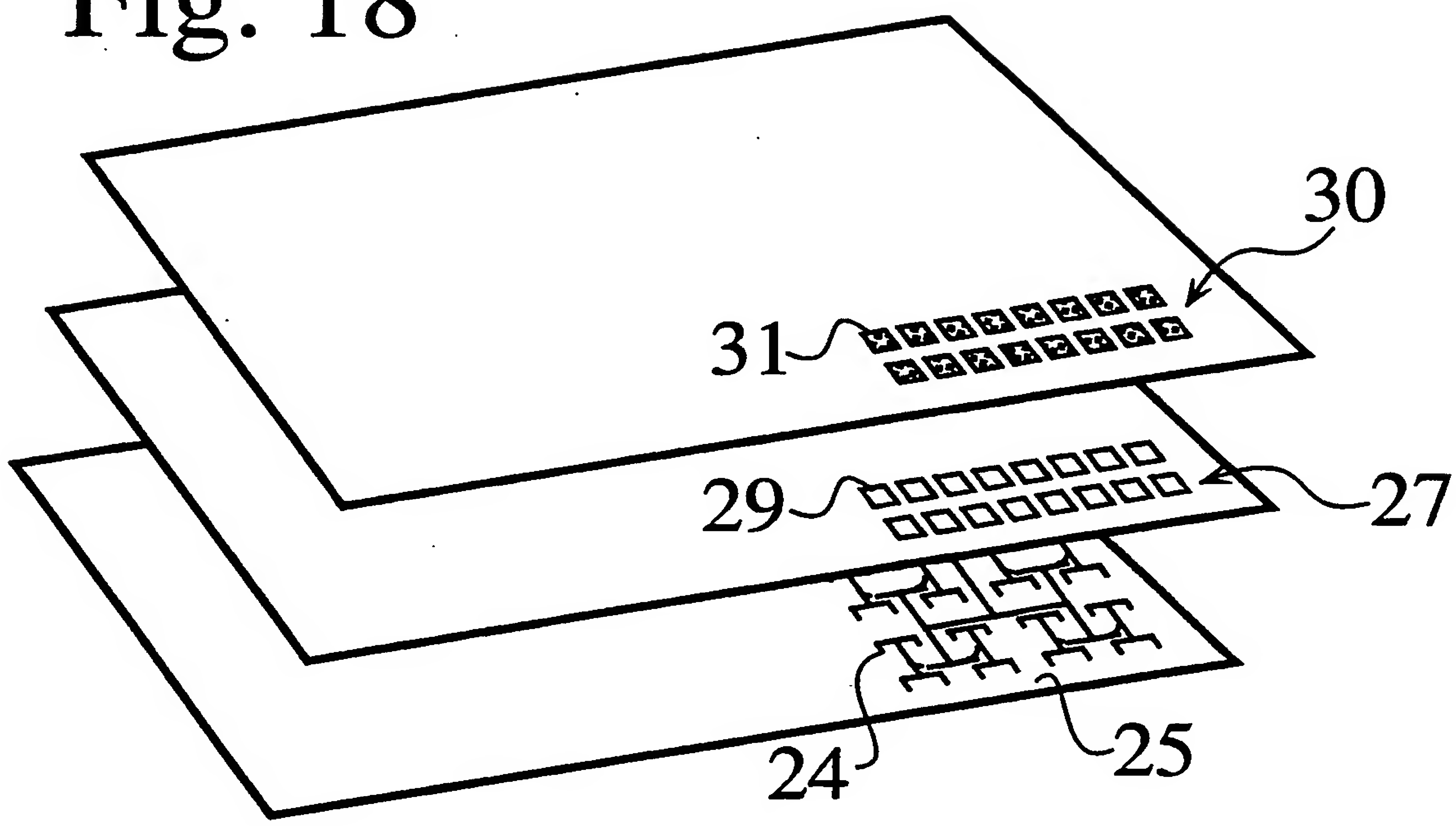


Fig. 18



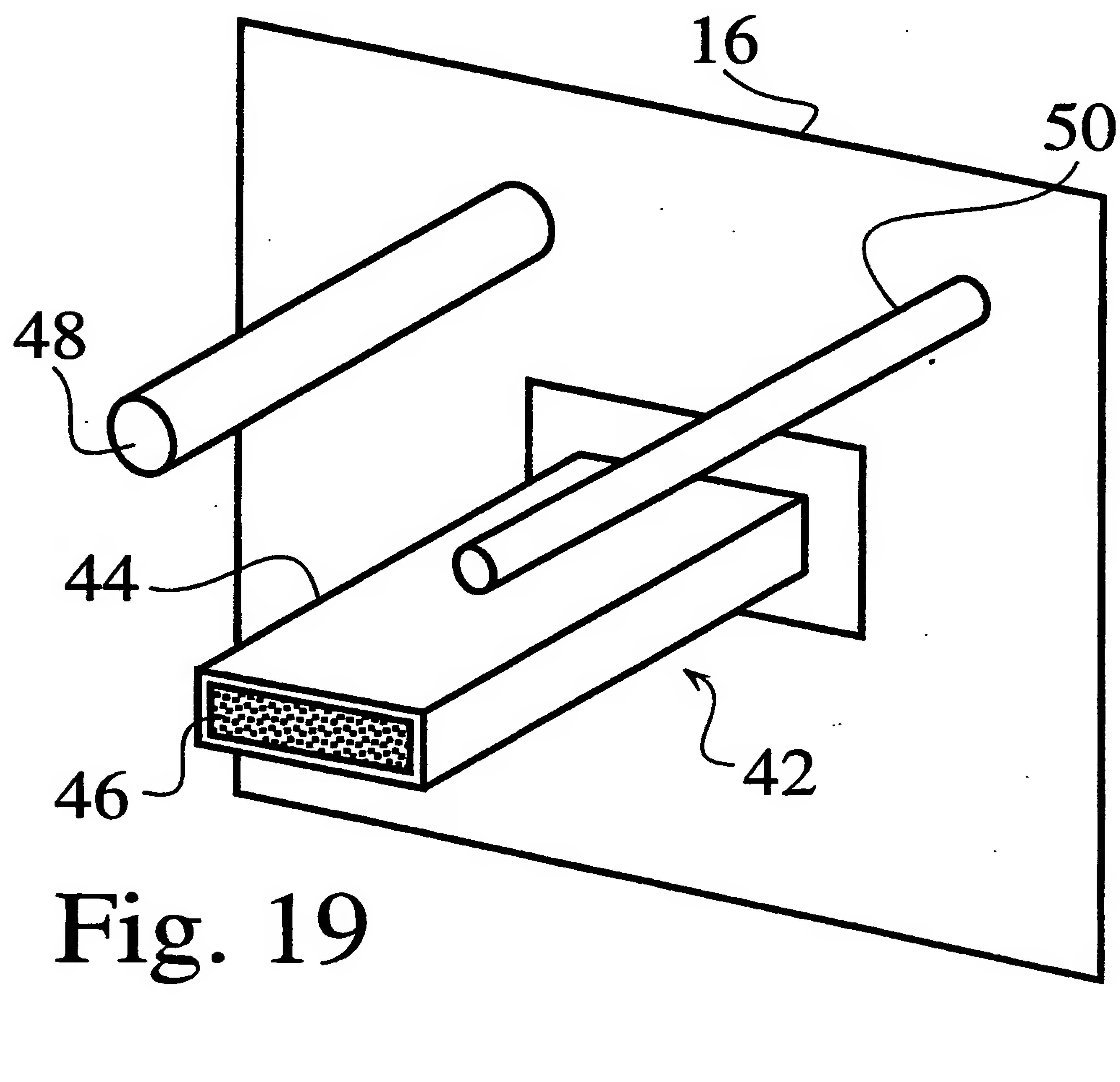


Fig. 19

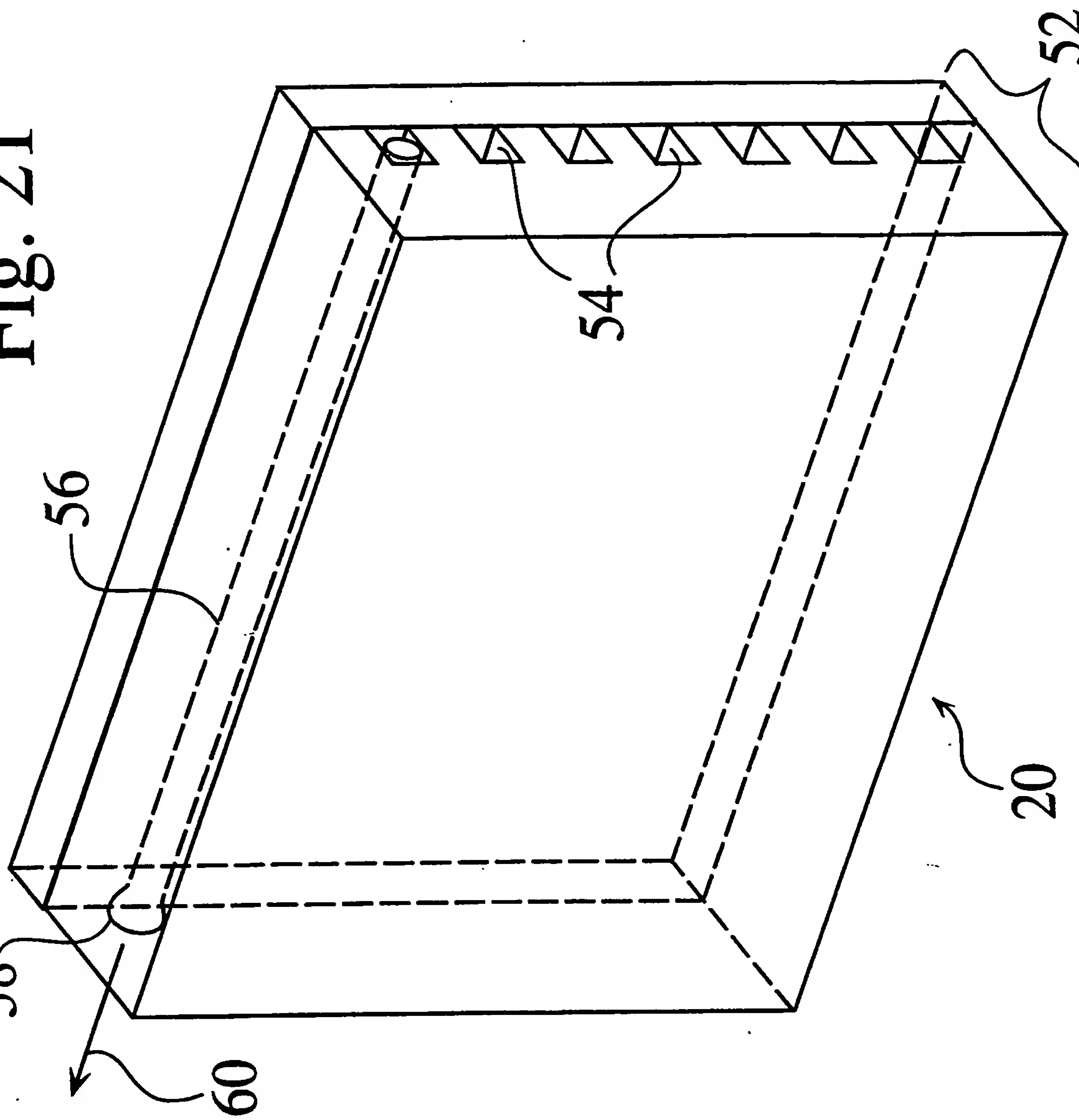


Fig. 21

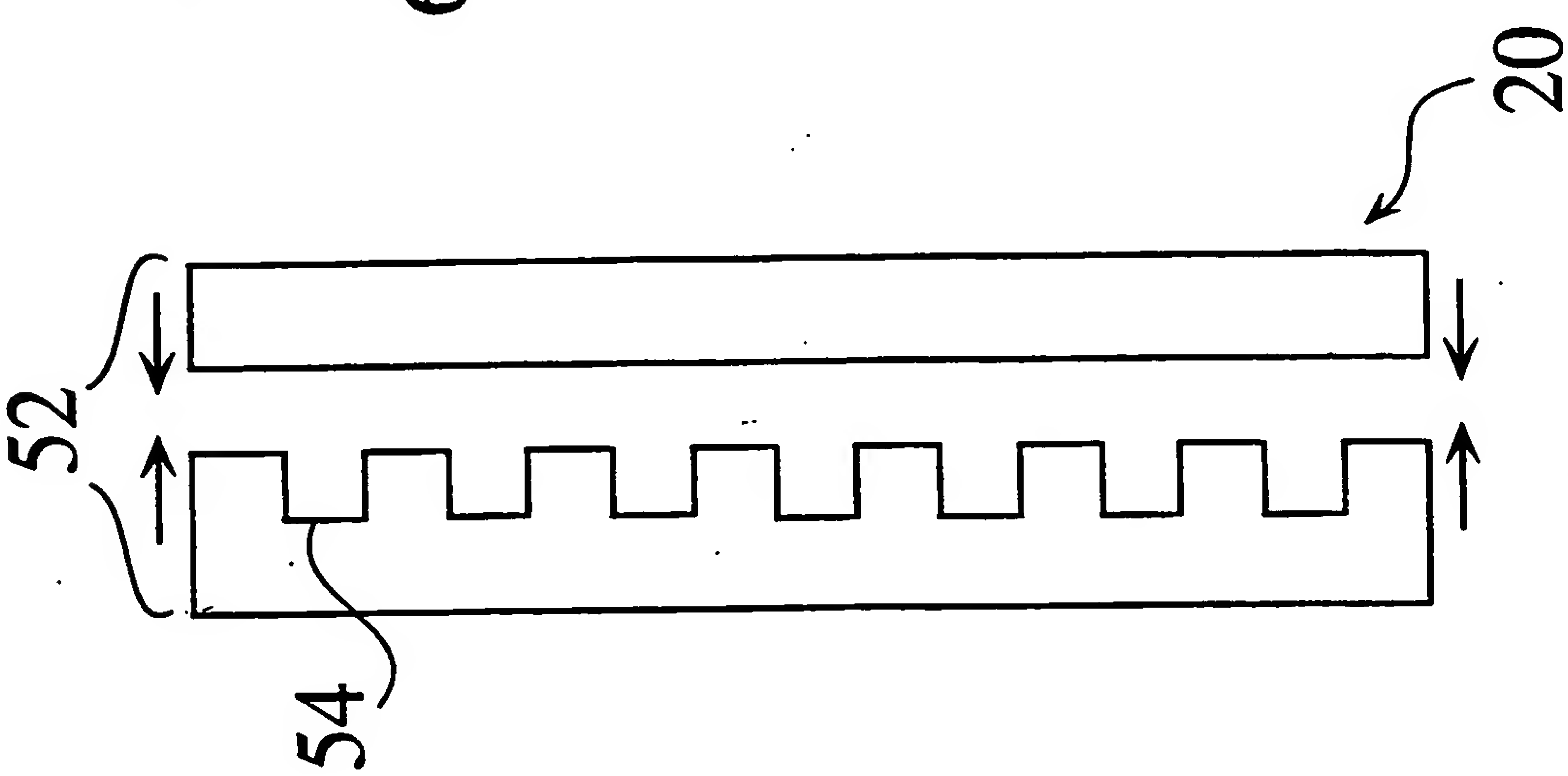
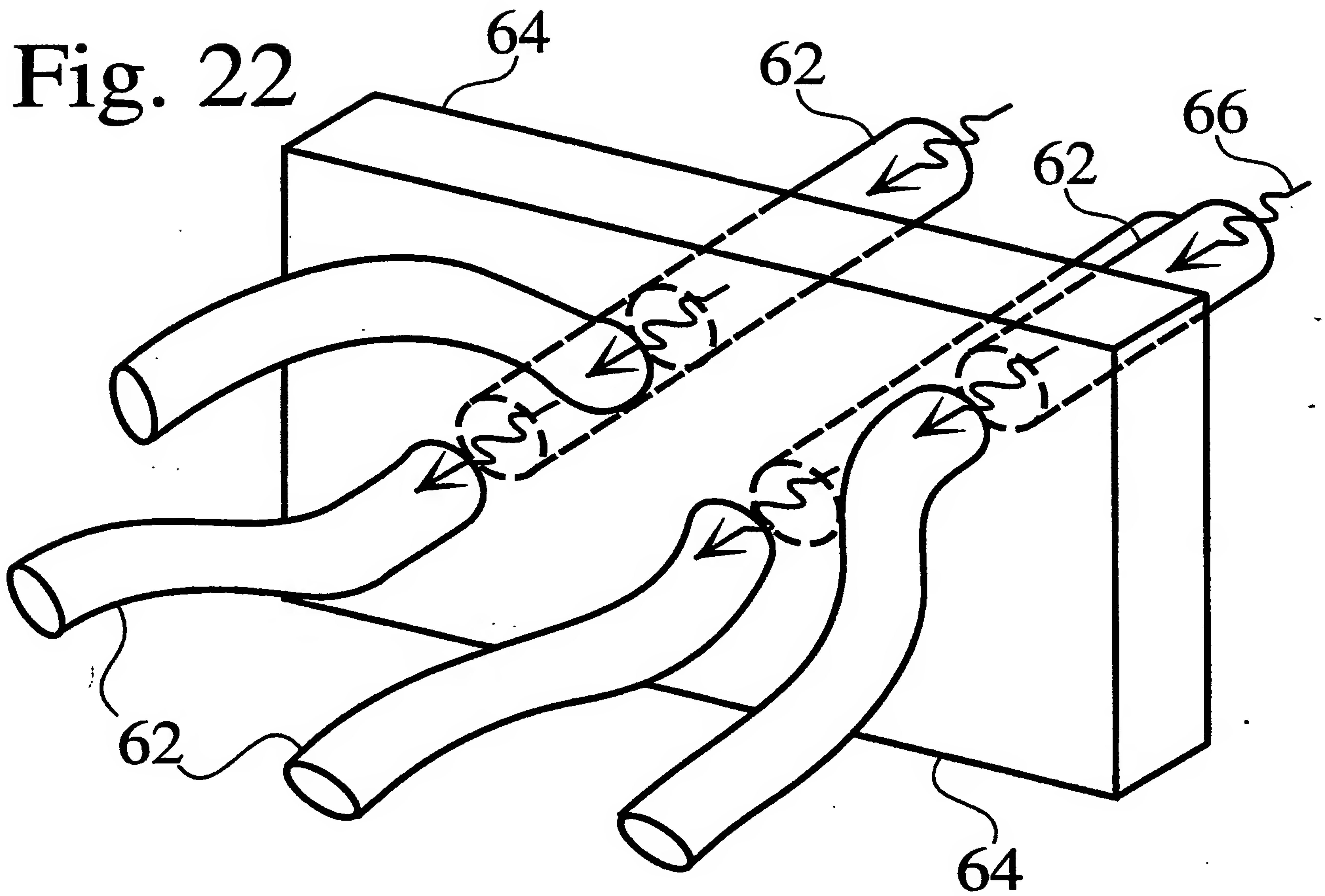


Fig. 20

Fig. 22



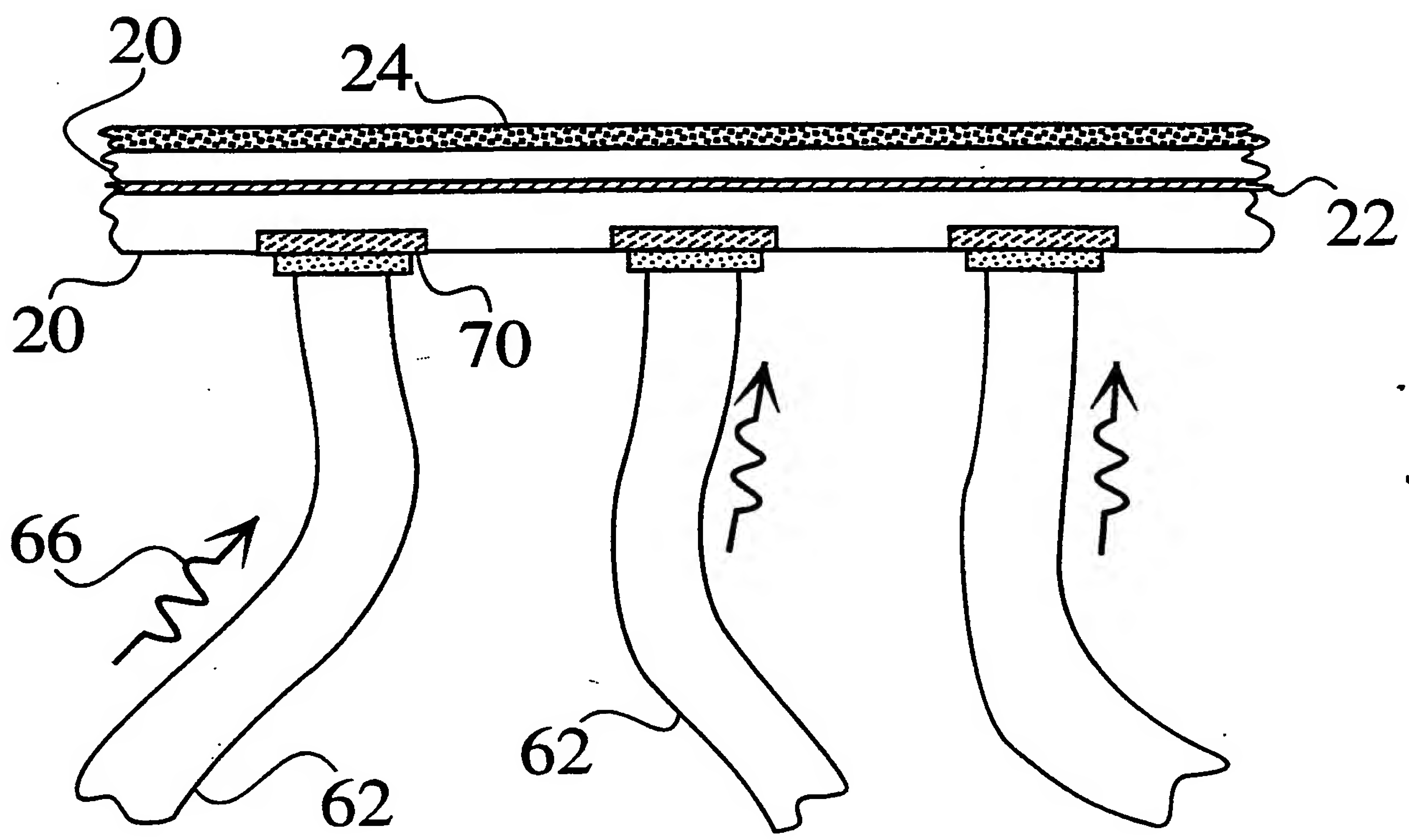


Fig. 23

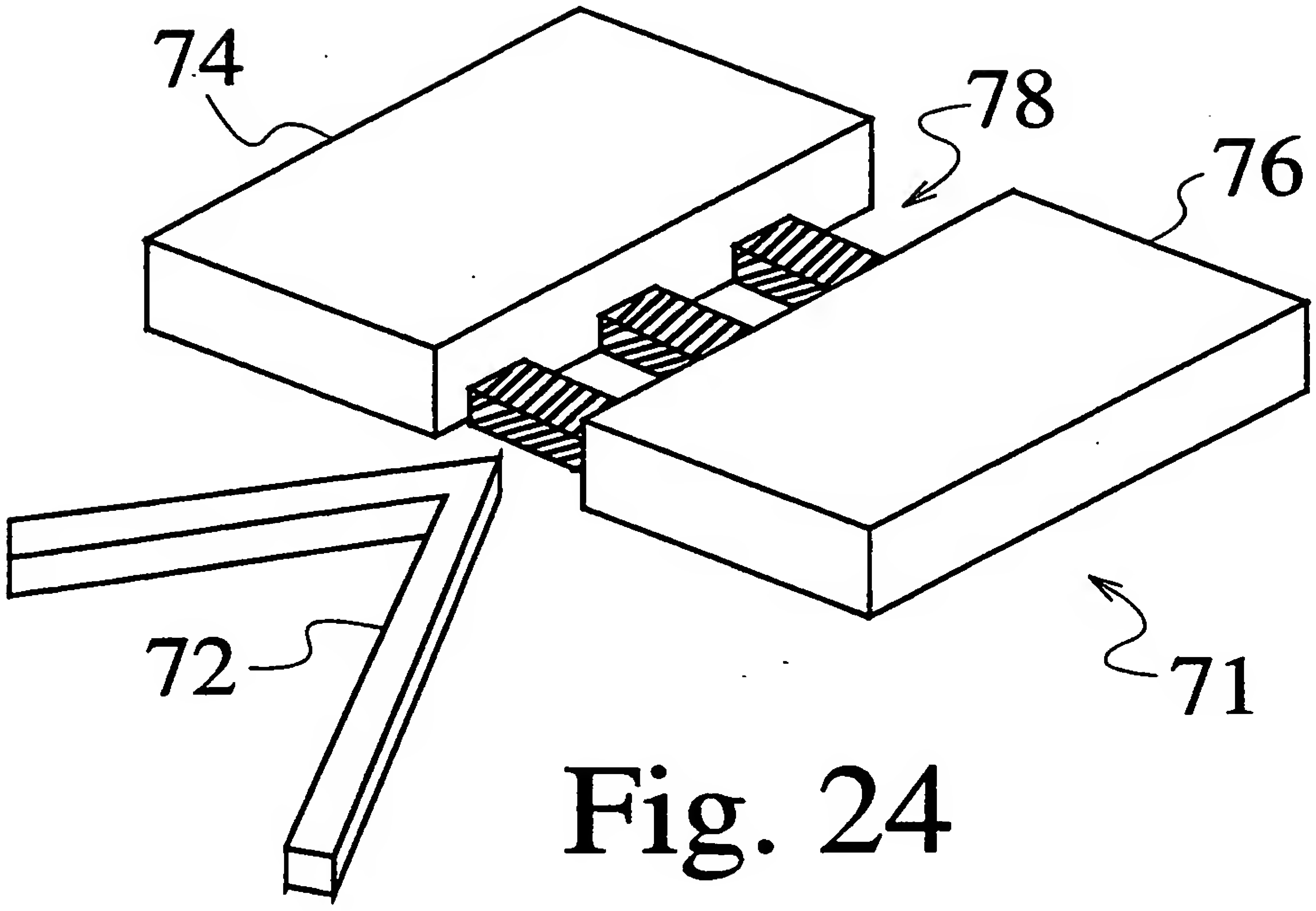


Fig. 24

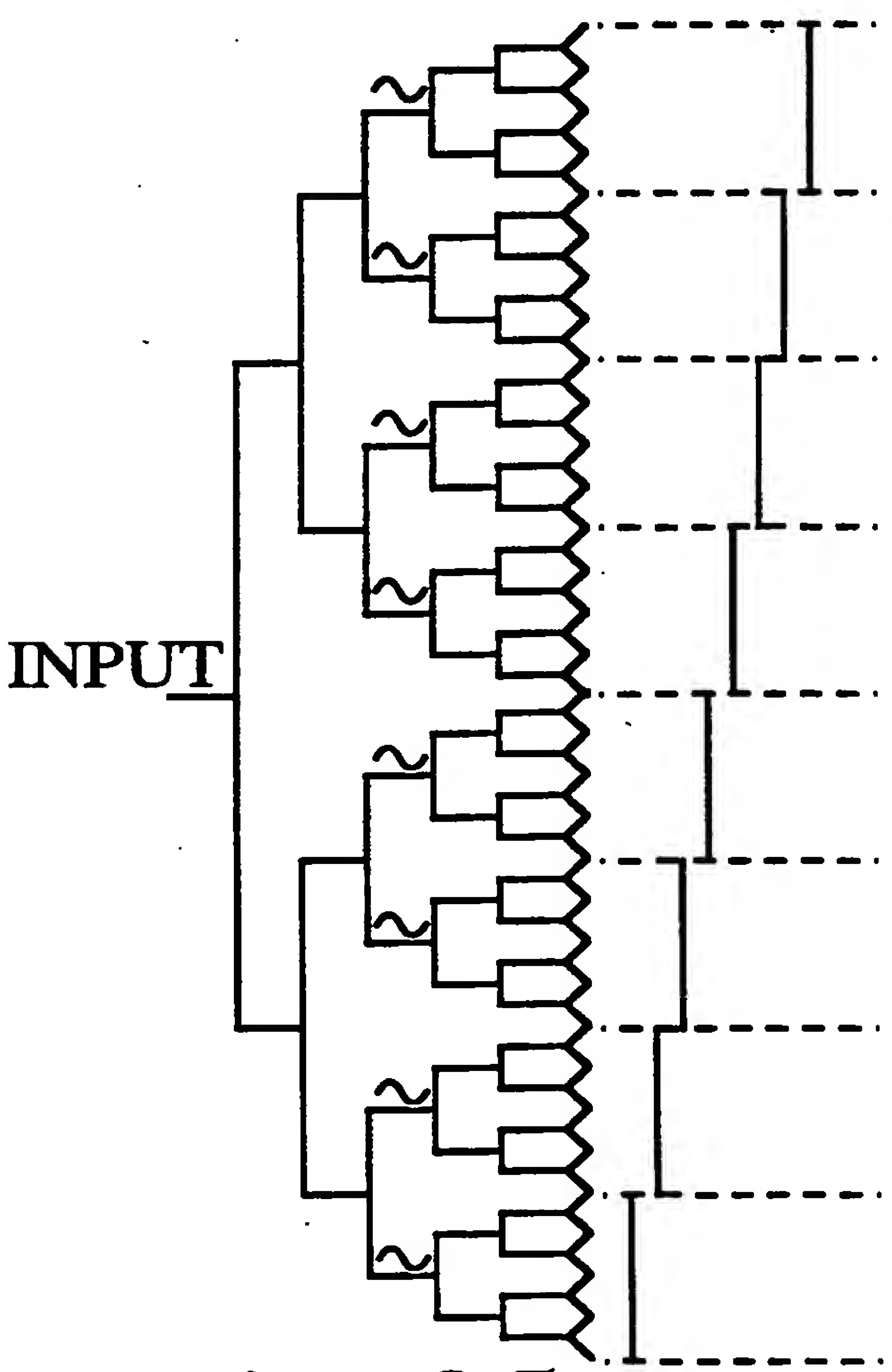


Fig. 25

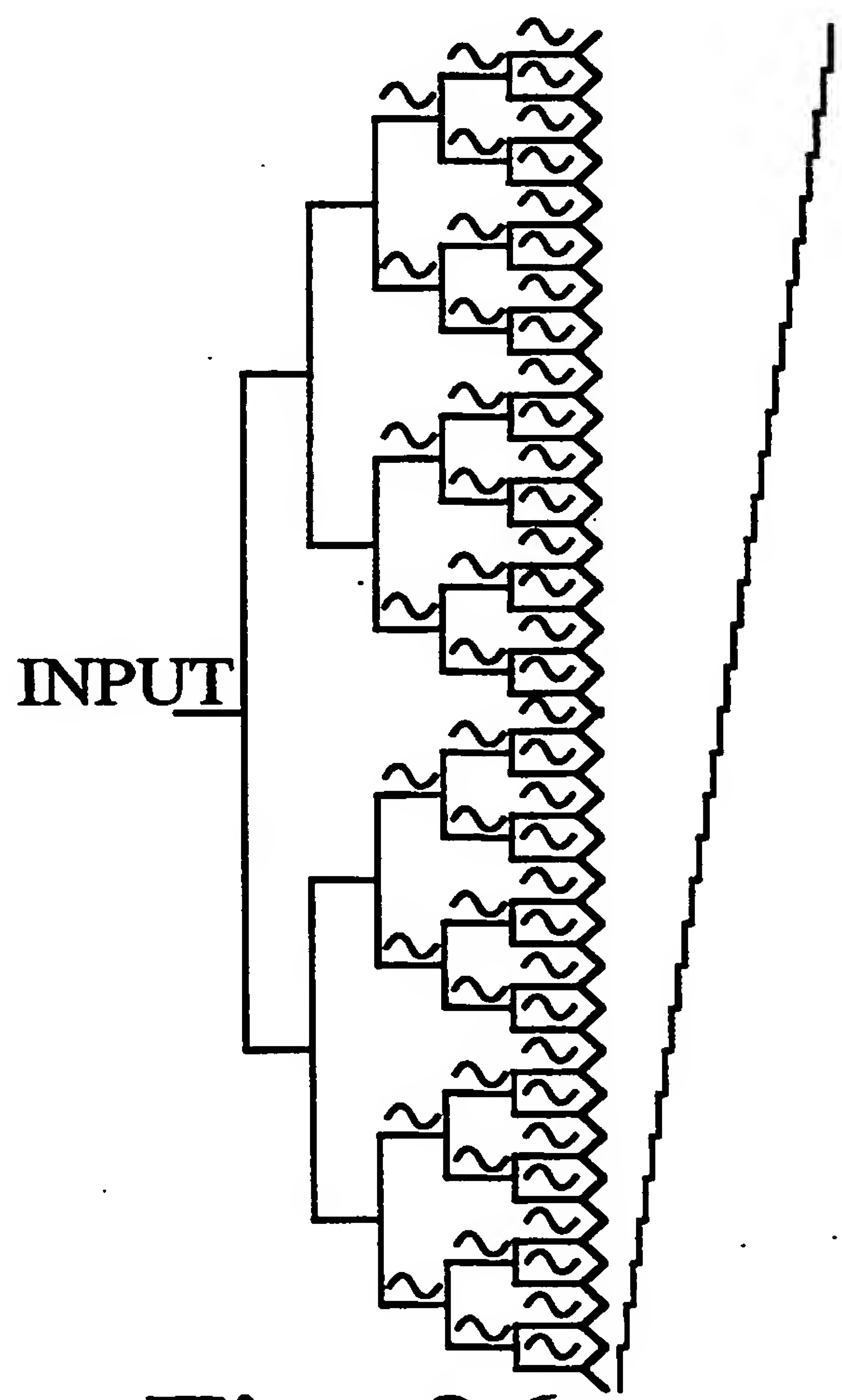


Fig. 26

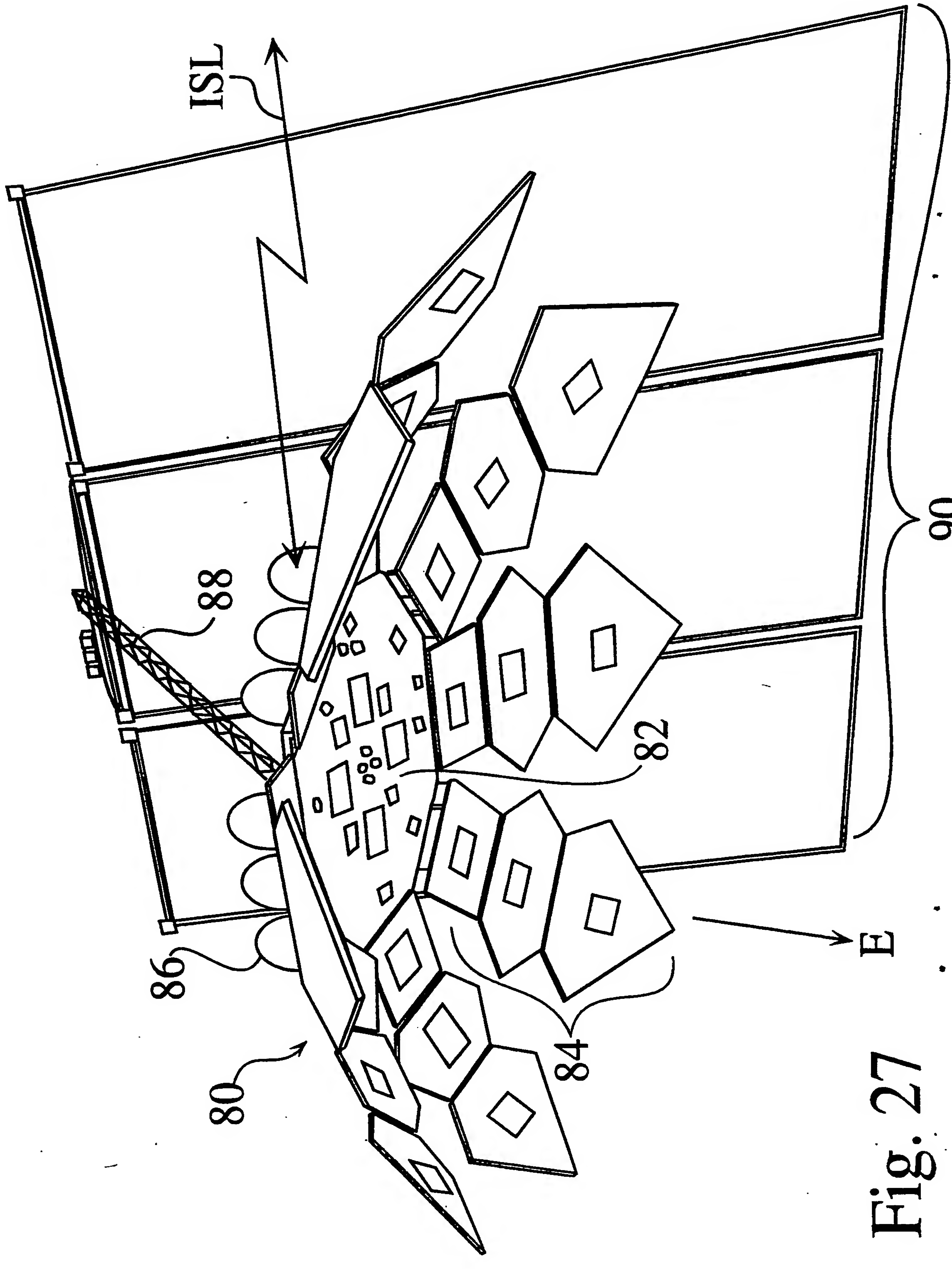


Fig. 27

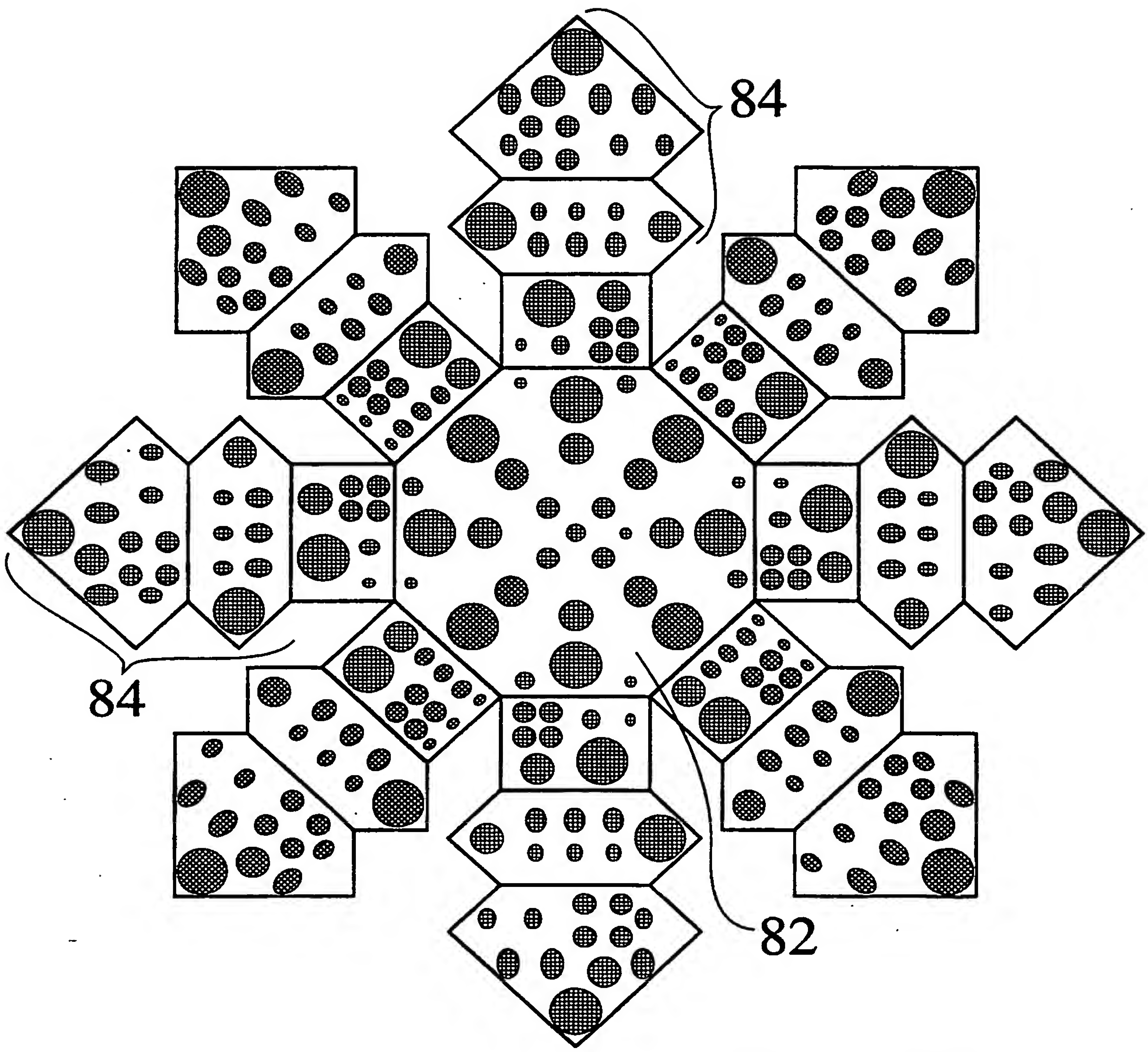
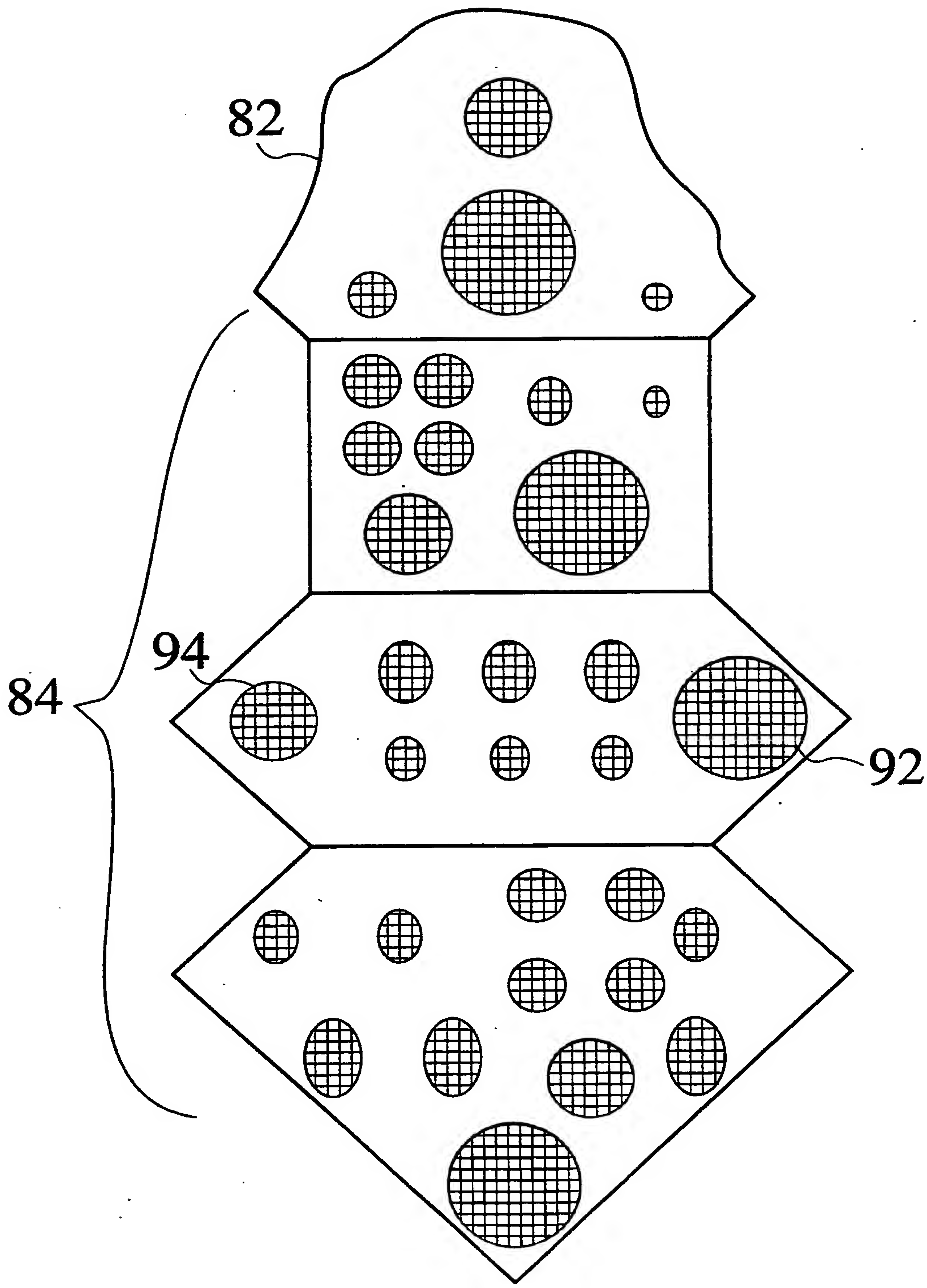


Fig. 28

Fig. 29



INTERNATIONAL SEARCH REPORT

International Application No PCT/US 93/06548

I. CLASSIFICATION OF SUBJECT MATTER (if several classification symbols apply, indicate all)[6]

According to International Patent Classification (IPC) or to both National Classification and IPC

Int.Cl. 5 H01Q25/00; H01Q1/28; H01Q1/36

II. FIELDS SEARCHED

Minimum Documentation Searched[7]

Classification System	Classification Symbols
Int.Cl. 5	H01Q

Documentation Searched other than Minimum Documentation to the Extent that such Documents are Included in the Fields Searched[8]

III. DOCUMENTS CONSIDERED TO BE RELEVANT[9]

Category °	Citation of Document,[11] with indication, where appropriate, of the relevant passages[12]	Relevant to Claim No.[13]
X	PATENT ABSTRACTS OF JAPAN vol. 015, no. 236 (E-1078)18 June 1991 & JP,A,30 71 706 (SANYO ELECTRIC) see abstract ---	1
Y	PROCEEDINGS OF THE IEEE vol. 80, no. 1, January 1992, NEW YORK US pages 183 - 193 HWANG 'Satellite Antennas' see page 191, paragraph C. ---	1
Y	US,A,5 105 200 (KOEPF) 14 April 1992	1
A	see column 3, line 12 - column 4, line 15; figures 1-6 ---	2
	-/--	

° Special categories of cited documents :[10]

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"L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)

"O" document referring to an oral disclosure, use, exhibition or other means

"P" document published prior to the international filing date but later than the priority date claimed

"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention

"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step

"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art.

"&" document member of the same patent family

IV. CERTIFICATION

2

Date of the Actual Completion of the International Search	Date of Mailing of this International Search Report
06 OCTOBER 1993	15. 10. 93
International Searching Authority	**Signature of Authorized Officer**
EUROPEAN PATENT OFFICE	ANGRABEIT F.F.K.

III. DOCUMENTS CONSIDERED TO BE RELEVANT (CONTINUED FROM THE SECOND SHEET)		
Category °	Citation of Document, with indication, where appropriate, of the relevant passages	Relevant to Claim No.
A	IEEE INTERNATIONAL CONFERENCE ON COMMUNICATIONS BOSTONICC/89 vol. 3, June 1989, BOSTON,MA pages 1595 - 1599 OKUBO ET AL. 'ETS-VI Experimental S-band Inter-Satellite Communications System' see the whole document	1
A	RADIO FERNSEHEN ELEKTRONIK vol. 41, no. 02, February 1992, BERLIN DD pages 101 - 104 PISCHKE ET AL. 'Supraleitende miniaturisierte Planarantennen' see page 101; figure 1	2
A	US,H,H653 (CONRAD) 4 July 1989 see abstract; figure	2
A	US,A,4 903 033 (TSAO ET AL.) 20 February 1990 see abstract; figure 2	2
A	EP,A,0 421 722 (MOTOROLA) 10 April 1991 see abstract; figure 8	3,6
P,A	WO,A,9 309 578 (CALLING COMMUNICATIONS) 13 May 1993 see claims 1-10; figures 1-8	1
P,A	IEEE ANTENNAS AND PROPAGATION SOCIETY INTERNATIONAL SYMPOSIUM 1992 DIGEST vol. 2, July 1992, CHICAGO,ILLINOIS,USA pages 974 - 977 HERD ET AL. 'EXPERIMENTAL RESULTS ON A 12-GHz 16-ELEMENT MULTILAYER MICROSTRIP ARRAY WITH A HIGH-Tc SUPERCONDUCTING FEED NETWORK' see the whole document	1,2

ANNEX TO THE INTERNATIONAL SEARCH REPORT ON INTERNATIONAL PATENT APPLICATION NO.

US 9306548
SA 77124

This annex lists the patent family members relating to the patent documents cited in the above-mentioned international search report.
The members are as contained in the European Patent Office EDP file on 06/10/93
The European Patent Office is in no way liable for these particulars which are merely given for the purpose of information.

Patent document cited in search report	Publication date	Patent family member(s)		Publication date
US-A-5105200	14-04-92	None		
US-H-H653	04-07-89	None		
US-A-4903033	20-02-90	None		
EP-A-0421722	10-04-91	CA-A-	2022854	03-04-91
		JP-A-	3139926	14-06-91
		US-A-	5017925	21-05-91
WO-A-9309578	13-05-93	AU-A-	3123893	07-06-93

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For more details about this annex : see Official Journal of the European Patent Office, No. 12/82

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